Possibilities for Using Hydrogen as an Energy Innovation and Accessibility Solution for Sustainable Development in Africa

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DOCTORAL THESIS

POSSIBILITIES FOR USING HYDROGEN AS AN ENERGY INNOVATION AND ACCESSIBILITY SOLUTION FOR SUSTAINABLE DEVELOPMENT IN AFRICA

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Declaration of Authorship

I, Edmond MKARATIGWA, declare that this thesis titled, "Possibilities for using Hydrogen as an Energy Innovation and Accessibility Solution for Sustainable Development in Africa" and the work presented in it are my own. I confirm that:

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SWANSEA UNIVERSITY

Abstract

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Possibilities for using Hydrogen as an Energy Innovation and Accessibility Solution for Sustainable Development in Africa

by Edmond MKARATIGWA

This doctoral research investigates the potential of hydrogen as a transformative energy solution for energy poverty and advance sustainable development in rural communities, aligning with the United Nations Sustainable Development Goal 7 (SDG 7). It highlights existing research gaps surrounding hydrogen's application and socio-economic impacts in African contexts. The study emphasises narrowing the largely binary and siloed approaches to technological and economic development, advocating for collaborative efforts between the Global North and South to eliminate dependency theory ideas, fostering equitable partnerships. The theoretical framework integrates corporate sustainability, sustainable development, and disaster risk reduction as mechanisms for poverty alleviation in Africa. Key objectives include assessing the global energy mix, identifying energy *accessibility gaps in Zimbabwe, and exploring hydrogen's potential as an alternative energy vector. Employing an interdisciplinary approach, the research developed a tailored Alkaline Electrolyser for use in Mukaratigwa Village. Its applicability was evaluated through a mixed-methods strategy that combined technical performance assessments with qualitative ethnographic research to gauge social acceptance. This methodology involved primary data collection from the study location and secondary data from key national energy suppliers and related policy-making institutions, accessed for analysis through a comprehensive literature review, including a global scan of original equipment manufacturers and associated hydrogen brands. Results suggest that hydrogen not only has the potential to improve energy accessibility but significantly mitigate deforestation, fulfilling sustainability criteria outlined in SDG 7. However, the study identifies critical barriers such as regulatory challenges and infrastructural deficits, underscoring the need for supportive public policies to stimulate investment in green hydrogen technology. Ultimately, this research informs policy and posits that hydrogen can diversify Africa's energy portfolio, contributing to the Sustainable Development Goals. It advocates for continuous collaboration, foster innovation, and further research to address challenges relevant to hydrogen deployment, aiming to enhance socio-economic development in climate-vulnerable communities.*

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LIST OF ACRONYMS AND ABBREVIATIONS

BEIS	-	Business, Energy and Industrial Strategy
CBOs	-	Community Based Organisations
DRR	-	Disaster Risk Reduction
EMA	-	Environmental Management Agency
ESMAP	-	Energy Sector Management Assistance Programme
EVs	-	Electric Vehicles
FDI	-	Foreign Direct Investment
GDP	-	Gross Domestic Product
GHG	-	Green House Gas
HET	-	Hydrogen Energy Technologies
HH	-	Household
HMEI	-	Association Hydro-Meteorological Equipment
IAEA	-	International Atomic Energy Agency
IPC	-	Infectious Prevention and Control
IPCC	-	Intergovernmental Panel on Climate Change
IRENA	-	International Renewable Energy Agency
LOHC	-	Liquid Organic Hydrogen Carrier
LPG	-	Liquified Petroleum Gas
MEC	-	Microbial Electrolysis Cell
NEDO	-	New Energy and Industrial Technology Development Organisation

NGOs	-	Non-Governmental Organisations
OECD	-	Organisation for Economic Cooperation and Development
OEMs	-	Original Equipment Manufacturers
OPEC	-	Organisation of the Petroleum Exports Countries
PHEVs	-	Plug-in Hybrid Electric Vehicles
PPA	-	Power Purchase Agreement
PPE	-	Personal Protective Equipment
PV	-	Photovoltaic
RE	-	Renewable Energy
SDGs	-	Sustainable Development Goals
SOEC	-	Solid Oxide Electrolysis Cell
SPSS	-	Statistical Package for Social Sciences
UN	-	United Nations
UNDP	-	United Nations Development Programme
UNISDR	-	United Nations Office for Disaster Risk Reduction
USAID	-	United States Agency for International Development
VIDCO	-	Village Development Committee
WADCO	-	Ward Development Committee
WGS	-	Whole Genome Sequencing

WIPO	-	World Intellectual Property Organisation
WMO	-	World Meteorological Organisation
ZERA	-	Zimbabwe Energy Regulatory Authority

CHAPTER ONE

1.1 INTRODUCTION AND BACKGROUND TO THE THESIS

The introduction to this thesis and chapter serves as a foundational overview of the study, outlining the socio-economic context and the critical role of energy innovations in achieving Sustainable Development Goal (SDG) 7: Affordable and Clean Energy. It addresses the urgency for transitions to renewable energy, particularly green hydrogen, as a complementary resource alongside solar and wind energy in developing countries and in the context of Zimbabwe. The chapter details the interdisciplinary approach taken to understand the matter under study, emphasising how complex global challenges necessitate insights from various fields, including energy science, social equity, and economic development. Section 1.1 of this chapter delves deeper into the background and significance of the research, while subsequent sections cover the theoretical framework guiding the study, objectives, the statement of the problem being addressed, methodological approach adopted for this research, and the specific context of Zimbabwe's renewable energy accessibility and utilisation. This comprehensive layout provides not only the rationale behind the study but also sets the stage for exploring practical pathways toward achieving sustainable energy solutions for alleviating poverty and fostering social equity.

1.2 Introduction

With pomp and fanfare, the United Nations (UN) launched the Sustainable Development Goals (SDGs) in 2015. Thus, it is envisaged the SDGs heralded a new era characterised by actions that had to lead to the attainment of huge strides in global poverty reduction. According to Swilling (2020), the advent of SDGs:

> Marked the start of the sustainability age – a time of crisis and transition when contested interpretations of sustainability provide the coordinates for future imaginaries. This does not refer to an age when sustainable modes of existence have been achieved in practice at the national and global levels. Building sustainable national and global systems may be the ultimate outcome if certain conditions materialise, particularly with respect to energy (Swilling, 2020: 3).

Transition to renewable energy is seen as a key pillar in transforming livelihoods. SDG 7 could be instrumental in unlocking renewable energy interventions towards clean and affordable energy. According to the Preamble to the document approved by the UN, "we are resolved to free the human race from the tyranny of poverty and want to heal and secure our planet" (Swilling, 2020: 3). This, however, can only succeed if we embrace Bruno Latour's (2018) "passions for change."

It is this study's conviction that humanity can make headway with the Sustainable Development Goals if the passions for change embrace novel interventions, especially in the renewable energy sector. The study explored the use of hydrogen as a complement to other renewable sources such as solar and wind. This might help towards fulfilling SDG

7, which will in turn ensure the development of agriculture, business, communication, education, health care and transportation.

The SDGs set out a framework to provide communities with levers for enhancing their livelihoods. As stated above, there is recognition of the imperfectness of the SDGs. Nevertheless, the SDGs, "perfect in their imperfectness" to borrow a phrase from Macqueen (2016), provided another opportunity for development. Against a backdrop of multi-agency aid, development organisations, and professionals, the alignment of the related complex interventions can help in effectively achieving these universal sustainability goals. This study thematically examined green hydrogen (H_2) innovation to establish the possibility for its practical implementation at local level, and at a smaller scale particularly at household level and for domestic purposes.

The study was anchored on interdisciplinarity. This was influenced by the realisation that today's hyper-complex problems the world faces, cannot be addressed through the lenses and efforts of one knowledge domain and discipline of practice. The novel study offered an opportunity to interrogate the catalytic role of energy, and in particular hydrogen, in developing countries' quest for sustainable development, and in particular, with a specific focus on Zimbabwe.

Zimbabwe, among other developing countries in the Southern Africa, has abundant yet largely untapped resources for more modern and cleaner renewable energy innovations and development. These resources are wind, solar and water for hydrogen. There is nevertheless, an increase in investments in solar energy at household and corporate levels, lesser investments in wind based electric energy and even least investment in the water based green hydrogen, across the country.

The primary sources of electrical energy in Zimbabwe are hydro and thermal. Nonetheless, continuous existence of thermal energy is already threatened by the rise and more inclinedly becoming mandatory a drive to cleaner energy innovations for addressing the carbon emissions induced climate change challenge. Continued new thermal energy infrastructure development is forecasted as only leading towards stranded assets in the near future and the longer term, as advocacy for phasing out hydrocarbons-fired power plants intensifies globally. These hydrocarbons are claimed as having worsening the global carbon footprint, further disrupting modern development approaches, threatening life on the planet and other planetary existence support systems. Not pre-empting the imminent risk being posed by disruptive technologies implies increased poverty as a result of the potential job losses and supply chain challenges in contrast to the sustainable development goals that seek to reduce the same.

Electrical energy supplied and accessed through the national mix of hydro and thermal energy grid is available only when the generators are switched on. Yet on the other hand, solar energy can be generated, supplied, stored and accessed on-grid and independently off-grid at both domestic and corporate levels. Thus, some electrical energy generated through the main hydrothermal power grid is lost without benefiting the broader society due to poor energy transmission networks and the inability to store excess energy when available. Hydrogen has the potential to close that gap due to its other favourable characteristics.

The existing electrical power energy is predominantly usable during power generation and shortly thereafter, except where it is stored in lithium batteries at appropriate levels. This implies continuous power generation for daily use, with a negative effect on lifespan of the generators, sustainability of energy supplies, and accessibility during energy use peak loads when some of the generators are down. Investment in solar energy generation technology and access supportive infrastructure are also weak in Africa. Hence, the necessity of the study that sought to establish a mechanism for closing that gap through the existing solution in the name of hydrogen.

As a result of the study, the global energy innovative solutions transitioning and refining challenges and their implications on poverty and energy access are revealed. Yet as with any new technologies, innovation must be embedded in a broader understanding of the end user. Therefore, ethnographic methods were employed to better understand energy provision's litigious aspects. Ethnographic research methods have been employed in many energy studies such as the ones by Axsen and Long (2022) and Pueyo and Maestre (2019) among others.

This chapter comprises background, theoretical framework, objectives, statement of the problem, methodology, population, and sampling. It further comprises a discussion on the study justification, study delimitation, limitations and the thesis outline, chapter summaries and conclusion.

1.3 Background of the study

This section largely provides the background to this research.

1.3.1 Energy as a Tool of Development

Energy plays a key role in development and sustainable development (Asghar, 2008; Stern, 2010; Bergasse, 2013; Lloyd, 2017; and McCollum et al., 2017), although Winther (2008) advances that energy alone is inadequate without other complementary mechanisms.

Choice of primary sources of energy and in particular their utilisation at any level is usually dependent on international and national factors (Winther, 2008; Yao, Luo, and Rooker, 2012; Ratner, 2018; and International Renewable Energy Agency (IRENA), 2021). On the other hand, levels of poverty also influence the choices of the energy to be used at that level. Poverty reduction efforts under the sustainable development imperative thus should facilitate socio-economic transitioning to cleaner energies in addition to the overall movement from the negative to the positive side of the development pendulum (UNDP, 2015; and World Bank, 2017). In the poverty reduction matrix, the predominantly sought interventions revolve around strengthening livelihoods and access to critical services. That has nevertheless brought about mixed successes and failures (Moyo, 2010; and Winther, 2008), posing a problem against meeting SDG 7 until sustainable energy supply chains are also incorporated into the rural resilience models.

More recently, livelihood strategies influenced by development and risk reduction scholars such as Wisner et al. (1994 and 2003) and Robert Chambers and Gordon Cornway (1992) have also been adopted to resolve the global poverty problem. In the same poverty reduction spirit, access to more renewable energy sources is key if sustainable development should be achieved (Energy Sector Management Assistance Program (ESMAP), 2020).

Industrialisation is also a universally agreed anchor to national economic development, growth, and the subsequent globally anticipated sustainable poverty reduction (Simandan, 2020). Industrialisation is nevertheless equally generally agreeable, the missing link against poverty reduction in most developing countries (UNDP, 2015; and World Bank, 2017).

1.3.2 The Potential of H_2 Implementation

The impacts of scaled-up and improved green electrolysis performance, fuel cell technologies, and hydrogen are yet to be translated into positively impactful socio-economic actions and implications on both developed and developing countries (IRENA, 2021).

Exploration of these issues in developing countries exposes implementation challenges that need to be well understood and tackled (ESMAP, 2020). This thesis offers a pilot opportunity for hydrogen production, use, scalability, and access sustainability in Africa and specifically in Zimbabwe.

There is a significantly growing volume of literature on energy and more specifically on hydrogen gas production, progress in hydrogen technology applications and refinement, as well as its socio-economic application imitability in different national contexts (Simandan, 2020; and IRENA, 2020). Winther (2008), however, cautions that new energy technologies must be tested at a smaller scale in different contexts first, before its ultimate global rollout, to ensure its social contextualisation for local adaptation and sustainable use.

1.3.3 Existing Interventions

In the quest for poverty and disaster risk reduction, climate change mitigation interventions are being implemented as a matter of urgency, due to the negative impacts of climate change on nations' developmental ambitions (ESMAP, 2020). Those interventions are driven by a number of stakeholders from non-governmental organisations, government, climate change specialists and philanthropists among others, and the corporate world (Simandan, 2020).

The Sendai Framework is an example of an international intervention that was framed by the United Nations Office to guide global implementation of Disaster Risk Reduction (DRR) actions in member states. It outlines seven distinct aims and four action priorities for preventing new and reducing existing disaster risks. With specific respect to climate change, the United Nations formed the Intergovernmental Panel on Climate Change (IPCC) to further the scientific understanding of anthropogenically induced climate change. The Energy Sector Management Assistance Program (ESMAP) is another intervention by the World Bank against energy poverty after realising that energy, poverty, and climate change are practically interlinked concepts. ESMAP provide toolkits, knowledge, and advisory services for policymakers, with the aim of promoting access to cleaner and cheaper energy without discrimination universally across all gender and race divides (ESMAP, 2022).

Nonetheless, those interventions also not been effective enough in balancing the process of tackling sustainable poverty reduction, industrial development and climate change. As a result, sustainable energy access and energy security remain far from being achieved universally and more specifically in the poorer communities of Africa (Winther, 2008). Thus, this study on the innovative hydrogen energy technology, sought to test the possibility for introduction and sustainability of cleaner energy supplies and access using the case of the peripheries of African society.

1.3.4 The Zimbabwean Context

Countries have varying energy sources, supplies, and accessibility challenges (Tonn et al., 2010; Kaseke, 2013; and Department for Business, Energy and Industrial Strategy, 2018). A study on Zimbabwe revealed that companies in the extractive industry harnessed diverse supplementary energy sources outside the normal dependency on their national electrical energy main grids (Mkaratigwa, 2020).

The behaviour by those entities was attributed to the climate change-induced hydro-electrical energy power shortages among other factors which warranted corporate adaptation for business sustainability (Ibid). Acute drought, shifting seasonality, low energy yields, and regionally shared hydroelectricity generation resources use restrictions, impacted the country's overall grid power performances in the country (United States Department of Agriculture, 2019).

To mitigate the energy gap, companies were resorting to diesel-powered generators, off-grid solar energy, and other sources. These are environmentally unfriendly sources of energy leads to pollution in the immediate ecosystem and inflicts further negative impacts on the overall net-zero targets since their alternative energy strategies include the burning of used vehicle tires. At the household (HH) level nevertheless, the use of biogas for domestic purposes is becoming more acceptable, even though using that gas as an alternative energy source notably presented its challenges (Agere, 2021).

By and large, energy challenges in Zimbabwe revolve around limited supply capacity and supply reliability, as well as limited accessibility and a high tariff, among others (Kaseke, 2013). There is ongoing advocacy and incentivisation for industrial and household investment towards cleaner renewable energy from wind, solar, biofuels, and hydro sources. Those and similar unmentioned innovations are anticipated to accelerate the reduction in the use of non-green (i.e., grey and blue) energy sources (IRENA, 2020; and Noussan et al., 2021).

Issues arising in Zimbabwe's energy sector are also experienced elsewhere. These issues vary from unsustainable electrical energy supplies to energy accessibility in connected communities; the large percentage of unconnected areas and agency corporate sense unsustainability (Bergasse, 2013).

As a result of some of the challenges noted above, there is a rising need to innovate and transition to sustainable energy supplies and accessibility options. The ideal transiting option options should be compatible with and supportive of the people, planet, and profit. Climate friendly energy accessibility have the potential to strengthen and open more opportunities for modern industrial and human development. Cleaner energy is also effective in poverty reduction and sustained income generation and has a boomerang effect on direct and indirect local energy supply and accessibility sustainability.

The energy profit aspect is difficult to imagine and realise in rural and peri-urban areas dominated by the economy of affection and the humanitarian aid dependence syndrome (Winther, 2008; and Simandan, 2020). That view buttresses the need for low-cost energy innovations that would ensure supply and accessibility sustainability, partially achievable through high embraceability translatable to the high utilisation rate which would economically justify the investment (ESMAP, 2020).

1.3.5 Energy SWOT Analysis for Zimbabwe

The following SWOT analysis provide an overview of the strengths, weaknesses, opportunities, and threats that exist in the targeted energy context of Zimbabwe. To come up with the analysis, both literature review (Government of Zimbabwe, 2019; Mzezewa and Murove, 2017: 27-29; and Anderson, 1997) and participant observations by the researcher were used.

SWOT Analysis

Strengths	**Weaknesses**
Existence of critical mineral resources: Zimbabwe has significant reserves of minerals essential for renewable energy technologies (e.g., lithium for batteries).	**Lack of Long-Term Renewable Energy Targets**: The absence of hydrogen-specific goals which inhibits strategic investment.
Peaceful Socio-Political Environment: Stable	**Inability to Enforce Cost-Reflective Tariffs:** Limits

governance supports collaboration on energy projects.	project viability and reduces investor confidence.
Availability of a Highly Skilled Labour Force: The nation boasts a skilled workforce capable of supporting various energy initiatives, including renewables, particularly hydrogen projects and technology implementation.	**Insufficient Research on Hydrogen Technology Potential:** Lack of comprehensive studies hampers informed decision-making.
Regional Grid Interconnection: Enhances potential for hydrogen export and integration with neighboring energy systems.	**Limited enforcement of environmental impact certifications for energy projects**: Weak enforcement risks environmental degradation.
Land-linked with a strong transport network: This infrastructure supports the distribution of energy resources (critical materials) and technologies to various regions.	**Complex Administrative Approval Processes:** Lengthy approvals deter investment and delay hydrogen project implementation.

Potential for Renewable Energy Utilisation: Abundant solar, water, and wind resources can effectively produce green hydrogen.	**Inadequate Infrastructure for Renewable Energy Projects:** Poor transmission and distribution networks hinder hydrogen solution integration.
Opportunities	**Threats**
Acute Energy Deficit: Existing energy crisis creates demand for hydrogen technologies and off-grid solutions.	**Over-reliance on Coal and Fossil Fuels**: Coal presence may slow hydrogen transition and renewables adoption.
Government Interest in Renewable Energy: Increased awareness may prompt support for hydrogen initiatives.	**Lack of Investment Incentives:** Insufficient incentives deter local and foreign investments needed for hydrogen projects.
International Financing and Partnerships: Collaboration opportunities with international organisations for funding green energy projects.	**International Sanctions and Perception:** Political and economic sanctions negatively impact foreign investment opportunities in hydrogen.
Abundant solar radiation, water, wind, and biodiversity: These resources offer vast potential for various renewable	**Climate Change Vulnerabilities**: Risks such as droughts may adversely affect energy generation and stability.

energy projects augmenting hydrogen implementation.	
Existing Education and Training Facilities: Leveraging local institutions to develop expertise in hydrogen technologies.	**Illicit financial flows:** Corruption and financial mismanagement undermine energy sector investments.
Development of Green Hydrogen Initiatives: Global shift towards the hydrogen economy offers Zimbabwe potential leadership in hydrogen production and export.	**Policy Inconsistency:** Frequent changes in energy policy characterised by limited accountability create uncertainty for stakeholders and investors hindering sustainable progress towards cleaner hydrogen energy solutions both at local and global levels.

TOWS Matrix	Opportunities (O)	Threats (T)
Strengths (S)	**SO Strategies** (Leverage strengths to capitalize on opportunities)	**ST Strategies** (Leverage strengths to mitigate threats)
• Existence of Critical Mineral Resources	1. Promote investment in hydrogen technologies using local minerals (attracting both local and foreign investment).	1. Advocate for stronger energy governance amidst coal reliance.
• Peaceful Socio-Political Environment	2. Collaborate on public-private partnerships for hydrogen projects.	2. Enhance energy security through regional grid connections.
• Availability of Skilled Labor	3. Develop workforce training programs in	3. Promote environmental regulations to support hydrogen initiatives.

TOWS Matrix	Opportunities (O)	Threats (T)
	hydrogen technologies.	
• Regional Grid Interconnection	4. Enhance hydrogen production facilities using renewable resources.	4. Engage in international partnerships to mitigate sanctions.
• 5. Potential for Renewable Energy Utilisation	5. Foster regional energy collaborations for hydrogen export.	5. Innovate on policy framework for stability in hydrogen investment.
Weaknesses (W)	**WO Strategies** (Overcome weaknesses by leveraging opportunities)	**WT Strategies** (Minimize weaknesses to mitigate threats)

TOWS Matrix	Opportunities (O)	Threats (T)
• Lack of Long-Term Renewable Energy Targets	1. Develop a comprehensive national energy policy for hydrogen goals.	1. Strengthen environmental impact assessments for sustainable projects.
• Inability to Enforce Cost-Reflective Tariffs	2. Implement funding mechanisms to foster hydrogen investment.	2. Create transparent policy frameworks to reduce uncertainty.
• 3. Insufficient Research on Hydrogen Potential	3. Conduct local studies on hydrogen technology potential and applications.	3. Diversify solutions beyond coal to enhance energy resilience.
• Complex Administrative Processes	4. Streamline processes using digital solutions for hydrogen approvals.	4. Engage in anti-corruption practices to secure funding for projects.

TOWS Matrix	Opportunities (O)	Threats (T)
• Inadequate Infrastructure	5. Raise public awareness to support hydrogen initiatives and projects.	5. Explore local manufacturing of hydrogen technology to mitigate cheap imports.

1.3.6 Examples of Energy Sources in Zimbabwe

The role of electrical energy is not fully experienced in many rural and urban communities in Zimbabwe. This is due to a huge national grid power supply deficit coupled with user poverty-related incapacitation. Nevertheless, there is an increased share of access to solar energy systems among rural communities.

Where electrical energy exists outside industrial sites and initiatives, it has not been optimally utilised, save for light load household consumption, although it is largely already viewed as more costly. Light loads usually exclude the use of household cooking and heating appliances.

Prandecki (2014) and ESMAP (2020) claim that key ways through which energy can contribute to sustainable development are expanded adoption and rollout of alternative renewable energy sources along with further improvements in the efficiency of energy production, supply, storage, and utilisation processes.

Communication and access to other essential services are progressively becoming more accessible through electrically powered online-friendly gadgets and technologies. Those without electrical energy are, to a greater extent, excluded from development. This reinforces the need for innovation and transitioning towards more sustainably accessible energy solutions that alternatively narrow down the rising electrical energy and other energy supply and demand gaps.

Hydrogen can help reduce electrical energy demand at the household level, potentially freeing the grid for other key energy uses such as lighting and the charging of electronic gadgets. This can allow more access to electricity in other communities, noting the electrification challenges encountered in other developing countries expressed in Winther (2008).

Solar power is mainly used for household lighting, charging cell phones, and recharging torch batteries. To a lesser extent, it is also used for powering electrical and electronic gadgets in domestic, commercial, and service centers such as shops, clinics, schools, and hospitals.

Alternatively, the use of Liquefied Petroleum Gas (LPG) as another renewable energy source is increasingly embraced at all levels nationally, despite its carbon footprint. Agere (2021) confirms that 13 million kilograms of LPG was used in the first three months of 2021 nationally.

Liquefied Petroleum Gas is used for cooking and heating, alleviating the household energy access gap left by grid electrical power and firewood. Generally, it replaces or complements even less cleaner energy sources such as firewood and coal. Acceptability of biogas as an energy source is almost failing beyond research institutions and protagonists' spheres, due to negative user perceptions and the unsustainable access to the energy sources.

In the first three months of 2020 and 2016 respectively, eleven million and one million kilograms of LPG were used and the statistics are lower than the 2021 figures (Agere, 2021). The rise in LPG utilisation presents a potential opportunity for hydrogen embraceability in the country. Communities require more access to innovations if they are to reduce the use of non-renewable energy that is unfriendly to the global climate change agenda.

Disaggregated data shows that in January, February, and May 2021, the country used 4,131,000 kgs, 3,872,756 kgs, and 4,995,281 kgs of LPG respectively (Agere, 2021). LPG has the potential to save in excess of 104 MW of electricity if the main grid electrical power consumers switch to gas (Ibid) among other clean cooking and heating energy alternatives. LPG possesses 35% and 20% less carbon footprint when compared to coal and other oils respectively.

There is therefore need for further innovation that secures sustainable access to energy for the good of the broader society in line with the Sustainable Development Goals and more specifically Sustainable

Development Goal Number 7 that positively impact women and the girl-child. Without such innovations, the unequal negative effect of carbonisation and the unequal energy access between the developed and the developing worlds will persist (Carbonnier & Grinevald, 2011; and ESMAP, 2020). As if these realities were not enough, the Covid-19 pandemic was another albatross around the neck of development globally and more specifically in Africa.

Essentially, the Covid-19 pandemic shone a glaring light on the fundamental fragility and inequalities of our societies and the crucial demand for transformation (Blundell et al., 2020). The Covid-19 pandemic broadly widened the inequality gap between rural and urban areas and more generally between the haves and have-nots of society, corroborating the urban bias and egalitarianism theories of development.

Hydrogen can be an alternative solution that anchors this study, which seeks to establish its propensity for being linked to other renewable energy sources as a nexus for socio-economic and human development. Since LPG and biogas are already used for cooking, heating, and lighting in Zimbabwe, this prepares the ground for hydrogen embraceability.

In addition, the Zimbabwe Energy Regulatory Authority (ZERA) has been working on measures to promote investment, safety standards, and codes for LPG (Agere, 2021). IRENA (2020) agrees that promoting investment in hydrogen is necessary while the development of safety standards, codes, and other regulatory frameworks remains inevitable. These new technologies should impact overall energy pricing and derivative economic opportunities (Ibid), further justifying innovative green energy studies.

1.3.7 Overview of the Study Location

The study was conducted in Zimbabwe, with a closer lens focused on Ward 9 of Shurugwi District, and in particular Mukaratigwa Village. Poverty prevalence in Shurugwi District stood at 66.5% in 2015 (Zimbabwe National Statistics Agency, 2015).

Mukaratigwa village in Shurugwi Rural is situated around 60 km from Shurugwi Town in the Midlands Province of Zimbabwe. Ward 9 has an estimated total of 1,816 households. Each household has an average of five (5) members, comprising both males and females of different genders and age groups (Zimbabwe National Statistics Agency, 2015).

Rural homes are chiefly made up of the elderly, youths, and fewer young adults. The youths are largely of school-going age and non-working able-bodied young adults. The settlement pattern in Shurugwi District, and particularly in Mukaratigwa Village where the study was situated, was predominantly linear. Principally, the village's homes are built alongside a road network. However, in some parts of the village, as was the case in many surrounding villages, settlements have been haphazard.

Subsistence farming and remittances from economically active family members living in urban areas are the livelihood mainstays of the communes. The ecosystem in the area encompasses smallholder plots, grazing areas, and mostly overexploited savanna indigenous forests. These forests are also used for firewood, brush wood fencing, poles for other modern types of fencing, and thatching among other uses. In the village during the time of research, there were eleven (11) households were connected to the national grid out of a total of ninety-eight (98) households, although 3 of them were not activated.

As documented in the case of some Zanzibari villages (Winther, 2008), the national grid for Zimbabwe was being fed from both hydroelectric and thermal power stations. A shopping center and a Catholic Church in the village were connected to the 50 KVA transformer that was also supplying the eleven village households. That powerline was further linked to Pakame Mission.

Pakame Mission is Methodist-owned and consisted of a secondary boarding school (forms 1 to 6) and a primary school (up to grade 7). This Mission is situated eight (8) kilometers south-west of Mukaratigwa village.

Dombotombo Secondary and Makonde Primary schools were also connected to the same powerline that linked the village to the grid. Both were day schools situated approximately three (3) kilometers to the eastern side of the village. The powerline from Makonde in addition, linked Gundura Clinic, which is five (5) kilometers to the north of the village. Gundura Primary School is also located about seven (7) kilometers to the north of the village and was still pending electrification. Rusike Primary School and Rusike Clinic were further linked through the same powerline. Moreover, they are located approximately six (6) kilometers to the east of the village.

Homes not connected to the grid mostly owned small solar energy systems for charging cell phones, home lighting, and powering other small and low energy-consuming appliances. Paraffin lamps are no longer predominantly used for lighting in the village.

Some households used cell phones for lighting and firewood for cooking and heating. A few households with electricity in their homes used it differently for cooking, heating, lighting, and powering household appliances, as noted above. Wind energy was being used only in a very few neighboring farms in the area, and LPG was inconsistently used by a handful of arguably middle-income households with a family member either working in schools, health centers, business centers, or growth points; and, less by the ordinary villagers. There is evidence that at its peak, wind energy has been used to power farms, many of which have now been converted into communal areas, although wind energy has never been used directly in this village.

Another shopping center in the same ward as the village is called Saizi. It is situated between Makonde/Dombotombo schools and Rusike Primary School. Saizi is approximately four and a half (4.5) kilometers from the village. The Business Center is also pending electrification just like another Business Center called Javangwe, which about eleven (11) kilometers to the north of the village.

Ironically, Jabangwe Business Center is within a five (5) kilometer radius of the electrified Chachacha Growth Point, which is sixteen kilometers to the north of the village. Shurugwi District Town is approximately 45 kilometers to the northwest of the village, while Gweru, which is the provincial city, is around 80 kilometers from the village.

In the same province, however, about 60 kilometers to the south-south-west of the village, there is another district town called Zvishavane that borders with Shurugwi District. There are also major mines dotted around the Shurugwi District, ranging from the platinum group of minerals to chrome and gold among others.

1.3.8 Local Social Action on Energy Access

The idea of the electrification of the village initially came about as a collective initiative of the working-class sons and daughters of the village, who were domiciled in the country and in the diaspora. The plan was hatched in 2003 following the government's launch of the rural electrification program. The program at inception prioritised communities within a five (5) kilometer radius from an existing powerline. That was later reduced to a mere kilometer radius from an existing supply source on a 60%:40% government to beneficiary funding model.

The plan encouraged syndication, which ideally was designed to lower the cost burden for the transformer, substation, and powerline installation as much as possible. However, in the context of Mukaratigwa Village, the burden of funding the 40% (US $35,000) contribution for the implementation of the project was ultimately borne by a single person. The eventual funder was part of the beneficiaries as well as a part of the group of working-class young people from the village.

The researcher had a good working relationship with the group members as a native of the Mukaratigwa Village and this research was recognised as another initiative in support of the Mukaratigwa Village's prospects for energy innovation and access. As a result of the villagers' positive reactions to this research, continued development of a good rapport with them assisted in accomplishing the implementation of the baseline survey. The researcher was however, cognisant to observe ethical research standards practices. Any mistakes or omissions that could be realised in this study were solely the researcher’s responsibility.

The village is endowed with abundant underground water and solar energy, which are both good sources of renewable energy. This offered room for integrated development and livelihoods sustainability. Clean and sustainable energy access has the potential to improve human and economic development when utilised effectively. Winther (2008), nevertheless, argues that the availability of energy does not automatically translate to human, economic, and livelihood development in some contexts.

1.3.9 Theoretical Framework

This study examined energy innovation through the theoretical lenses of Sustainable Development (Bode, Singh and Rogan, 2015; Burbano, 2016; Gartenberg, Prat and Serafeim, 2018; and Posen and Martignoni, 2018); Corporate Sustainability (Montiell and Delgado-Ceballos, 2014; Flammer, 2015; and Gupta and Misangyi, 2018); and Disaster Risk Reduction (Twigg, 2015). These theories are anchored in the poverty reduction thinking advanced in Wisner et al. (1994, 2003) and Chambers and Cornway (1992) among others.

1.4 The Theory of Sustainable Development

The concept of 'sustainable development' is variously defined by both scholars and practitioners. It is also critically viewed by some as an ambitious yet unachievable mirage (Jabareen, 2008; and Prandecki, 2014). It is advanced as a mirage because there are no universal costs toward its achievement and it is often inadequately defined by negative geopolitics, which makes greenwashing at the implementation level rife. Moreover, implementation triggers an influx into the new energy innovation matrix arena by opportunists and vultures, creating greenflation that renders sustainability policy and procurement standards far outstripping the availability of technology.

Relating to energy within the sustainable development domain, more critical in developing countries is social tolerance regarding the cost of access to the source of energy and the cost of its acquisition. In addition, sustained assurance of energy availability for use and integration of new innovations into the existing infrastructure is key. Permanent energy access can be achieved through energy savings, more efficient solutions and technologies, as well as increased reliance on renewable energy (Winther, 2008; and Prandecki, 2014).

The sustainable development thinking is rooted in the theory of progress that focuses on transitioning forward towards a more perfect future. It is consequently in that thinking, a departure from the imperfect past. Emmanuel Kant among the fathers of deontological ethics, advances the same ideas in stating that life is a continuous process full of change and transitions (Eisenmayer, 2018; and Kraus, 2020). The background of the concept is that the cycle of world history is now so large that it is difficult to see history's beginning and end (Mitcham, 1995).

Underpinning sustainable development, in the same respect, is The Club of Rome's report, 'Limits to Growth' (1972). The report noted that technological development and societal development cannot simply continue as they have been in the past 200–300 years (Meadows et al., 1972). Therefore, comparing present advancements with the past, without considering the future except as an open-ended possibility for further growth and improvement is viewed as a source of increasingly intractable problems (Kraus, 2020).

In this context, catastrophe is anticipated to occur as a result of current forces that make the present better than the past, as supported by the current quest for progress (Kraus, 2020). As a result of that realisation, there stems a shift of emphasis from what should not be done (in the sense of 'Limits to Growth') to what should and can be done in the sense of the 'sustainable development' concept (Kraus, 2020).

The ‘sustainable development debate was initiated through two reports: World Conservation Strategy (1980) and Our Common Future (1987). In the World Conservation Strategy (1980), development is defined as modification of the biosphere and application of human, financial, living, and nonliving resources to satisfy human needs and improve human life (Mitcham, 1995; and United Nations Development Programme, 1994).

Development is meant for the people, and not necessarily for the things or natural resources being conserved (Mitcham, 1995). Hence, the rise of enlightenment associated with the human development conceptual thinking in the modern development discourse (United Nations Development Programme, 1994). Interrogation of this view further leads to the question of the end of these interactions between what Sen Amartya named beings and things (Amartya, 1992). The question arises from noting that all being done is for the purpose of saving beings.

The seminal Our Common Future (1987) Report ushered the Sustainable Development concept into the international arena. The Our

Common Future (1987) Report is the last of the Brundtland Commission (Independent Commission on International Development Issues that was chaired by Willy Brandt, former Prime Minister of West Germany). It came after their first report, the Common Crisis (1980) (Brandt, 1980), among others. The Commission employed the economic rhetoric of 'the commons' to establish the global environment as a world-commons, thereby creating the object of global environmental governance.

Another document of significance in this regard is the Common Security (1982) report by the Independent Commission on Disarmament and Security Issues chaired by Olof Palme, former Prime Minister of Sweden. These reports, and particularly Our Common Future, were not addressing only governments and development specialists, but also all sections of society (Barkin, 2006; Mitcham, 1995; and United Nations, 1987). The commission employed the economic rhetoric of the commons to establish the global environment as a world-commons and thereby create the object of global environmental governance.

In "The Tragedy of The Commons" (1968), Hardin argues that it is difficult to reach a point of energy sustainability as long as there is freedom to breed, leading to continuous population growth. He states, “It is the acquisition of energy that is the problem,” asserting that even in the presence of an infinite source of energy, greediness and population growth produce an inescapable problem. Society will always grapple with the challenges of harnessing energy, equitable distribution, and maintenance.

The claim above universalises life claims beyond the limits of institutions, regimes, and states by cutting across the globe (Barkin, 2006; and United Nations Development Programme, 1994). That eventually led to new questions of human responsibility, limitations to sustainable development, and the universality of Human Rights (United Nations, 2015). The realisation of responsibilities of men and women gives hope that both technology and social organisation can be managed and improved to make way for a new era of economic growth (The Brundtland Report, 1987).

1.4.1 Ideologies of Sustainable Development

In that background, Amartya (1992) viewed development as freedom, particularly freedom from want and fear. This highlights the need to address other limitations to development imposed by inequalities. What then is sustainable development and what can secure freedom from fear and want? Human security can be seen as a prerequisite for the full enjoyment of human rights.

The four basic characteristics of human security are universalism, interdependence, early prevention, and people-centeredness. This concept of sustainable development is construed from different philosophical views cutting across libertarians and egalitarians, among others. In addition, key sources of threats to human survival and, thus sustainable development in general, are numerous. These include limits to economic security, food security, health security, environmental security, personal security, community security, and political security in the contexts under consideration (United Nations Development Programme, 1994).

The philosophical views around development are diverse and can be grouped into libertarianism and egalitarianism, as noted above. According to Karnani (2010), libertarian views underemphasise the role and responsibility of the state in poverty reduction. These views overemphasise the bottom-of-the-pyramid approach whereby free markets are advanced as the best approach for reducing poverty in society. Libertarian views have less consideration for legal, regulatory, and social mechanisms for protecting poor vulnerable consumers (Barnett, 2004). Although there is a tendency to categorise people based on their beliefs and behaviors, it is critical to take into account their diverse thoughts to unlock their potential to guide humanity to development.

For example, microcredit is a small-business finance product advanced in libertarian economic thought, which posits that individuals are resilient, creative entrepreneurs. The result is the creation of small businesses that can generate employment for the poor and value-conscious consumers. However, the approach is arguably harmful to the poor, although it illustrates how liberty and free markets operate (Barnett, 2004).

Egalitarian economic thought advances that as a matter of justice, individuals should be equally well-off in certain circumstances. Equality, in that view, refers to the distribution of goods equally. This study adopted the definition by Paul (2019) that equality can be defined as treating every individual in the same manner irrespective of need and requirements. Acknowledging that some inequalities and differences are unavoidable and justified, Egalitarians postulate that the cardinal good had to be identified (Barnett, 2004). This is identified as access to welfare and opportunities, advantages, capabilities, resources, or something else along that continuum.

Equal access to resources is, however, counterproductive due to human behavior. Even in the presence of equal access to resources, some may be too lazy to work, creating room for inequality. Hence, growth becomes a personal responsibility, choice, and effort within given circumstances, referencing differences in the distribution of goods and particularly material wealth as part of social justice in society. In its conservative approach, egalitarianism accepts that values such as solidarity can be traded off against equality where necessary (Hiebaum, 2015).

This study reasserts the four basic characteristics underpinning sustainable development as discussed earlier. These are universalism, interdependence, early prevention, and people-centeredness (Amartya, 1992; and United Nations Development Programme, 1994). They largely fall into a constructionist approach to societal interventions.

The social constructionist approach broadens and informs actions and programmes, including engagement with government and civil society (United Nations Sustainable Development Group, 2015).

Zimbabwe's political and economic systems have evolved over time, and its ideology has been influenced by various factors. Zooming in on its historical context, the country has experienced different ideological phases as follows:

- Pre-independence (1965-1980): Rhodesia, the predecessor to Zimbabwe, was a British colony with a white minority government, which was inherently unequal and discriminatory.
- Post-independence (1980-1990s): Zimbabwe adopted a socialist-oriented economy and a one-party state, with Robert Mugabe's ZANU-PF party dominating politics.
- 2000s-present: Zimbabwe transitioned to a mixed economy, but the government's authoritarian tendencies and economic mismanagement have persisted.

Currently Zimbabwe's ideology is a mix of:

- Authoritarianism: The government exercises significant control over the economy, media, and civil society;
- Nationalism: Emphasis on Zimbabwean identity and sovereignty;
- Socialism: State-owned enterprises and government intervention in the economy, and;

- Patronage: Ruling party's influence over economic opportunities and resources.

Zimbabwe is neither purely libertarian nor egalitarian. In fact, its ideology is a complex blend of authoritarianism, nationalism, socialism, and patronage, with some libertarian and egalitarian elements. However, the country's governance and economic systems require significant reforms to achieve true equality and freedom.

1.4.2 Disaster Risk Reduction

Disaster risk reduction is the concept and practice of reducing disaster risks through systematic efforts to analyse and manage the causal factors of disasters. By and large, that includes reduced exposure to hazards, lessened vulnerability of people and property, responsible management of land and the environment, and improved preparedness for adverse effects (UNISDR, 2009; and USAID, 2011).

These efforts can yield more results if key sustainable development cross-cutting issues are earnestly considered and wisely practiced. Therefore, universalism, interdependence, early prevention, and people-centeredness must be incorporated in the process as already advanced for the implementation of sustainable development interventions (Amartya, 1992; and United Nations Development Programme, 1994).

Disaster risk reduction is among those key pillars for the achievement of sustainable development. Disaster risk is increasing in developing countries as a result of hazard build-up and increased vulnerability due to socio-economic factors illustrated in the Pressure and Release model as outlined in Wisner et al. (1994; 2003).

This study therefore embraces the disaster risk reduction (DRR) thinking in exploring the solar-powered electrolysis process to generate green hydrogen usability pathways for vulnerability and hazard reduction in a developing country context. DRR seeks to reduce underlying societal risk factors and promotes the use of knowledge, innovation, and education to build a culture of safety and resilience at all societal levels (Twigg, 2015).

Recognition of the necessity for disaster risk reduction is authoritatively advanced by the Risk Society theoretical thinking posited by Ulrich Beck (1992). In Beck's view, modernity, industrialisation, democracy, and globalisation are aspects of development at the core of threats facing humanity and the ecosystem that should sustain them. This endangers all of society and leads to questions around whether development is for the people or against the people (Barkin, 2006; and United Nations Development Programme, 1994).

These questions are directed to the general populace beyond governments and institutions alone (Barkin, 2006; Mitcham, 1995; and United Nations, 1987). Failure to address these issues exposes people to various insecurities (United Nations Development Programme, 1994), yet development should be for the people (Mitcham, 1995).

1.4.3 Disaster Risk Reduction and Human Security

Human security is at the center of sustainable development (United Nations Development Programme, 1994), already complicated by the process of globalisation, which is agreeably associated with high social costs and multiple forces that create fear and insecurity. Nevertheless, human security is criticised for lacking conceptual clarity and an exclusive paradigm to facilitate precise intellectual discourse.

Despite that criticism, the human security paradigm stems from experiences of failing developmental policies among states and nations globally. These policies caused increased ecological degradation, population explosion, extreme poverty, health hazards, and the slowed-down democratisation processes. In narrowing the definition of human security, scholars generally define it as the human expectation of years of life without experiencing poverty in generalised (Sudha, 2007).

Underscoring the centrality of people in development and sustainability, Alkire (2003) claims that human security takes its shape from 'self', making the human being the vital core to be secured. This assumption acknowledges that the institutions supposed to protect the vital core are not sacrosanct and thus will not safeguard every aspect of human security. Hence, the destructive nature of most aspects of development ensues.

Disaster risk reduction is a strategy for preserving human security (UNISDR, 2009; USAID, 2011; and Twigg, 2015). The sustainable livelihoods framework developed by Robert Chambers and Gordon

Cornway (1992), among other newer versions, and the Pressure and Release Model by Wisner et al. (1994; 2003) have informed risk reduction interventions in both rural and urban areas.

The question, however, remains: Have they been effective enough to protect the vital core? Whatever the case, efforts are being made, as Alkire (2003) notes that human security is a process, not an end. These efforts, therefore, are complementary. Furthermore, they should be informed by local perspectives on what constitutes the vital core to the referent communities, including opportunities to accomplish what is of particular value to specific people (Barkin, 2006; and United Nations Development Programme, 1994).

Unfortunately, in development parlance, those on the lower rungs may not value what is ahead, which they have not been exposed to and which they do not know exists. These may need some form of support, perhaps through the agency (Alkire, 2003).

Alkire (2003) brings about another interesting aspect relative to the vital core, which is human security, generally implied to mean the human being's right to survive. Questions around the first priority of the disaster risk reduction strategy's referent object arise when considering the binary hazard and vulnerability divide of the Pressure and Release model (Wisner et al., 1994; 2003).

Alkire (2003) leans toward prioritising the human side of human security, giving secondary importance to the threat side. That, on the other hand, implies prioritising human freedom already embedded in the language of the vital core. How is it supposed to be done, given that feasibility is the main challenge experienced in implementing the strategies? As a result, freedom from fear and want is sometimes achieved through broader approaches that recognise their intrinsic importance (Sen, 1992).

The choice of the route can, however, be far-reaching, contested, and complex, as witnessed in other contexts such as those noted in Moyo (2010) and the case of electricity installation in Tanzania (Winther, 2008). Further, since sustainable development transcends institutions and comes down to people, studies focusing on what can directly change people's lives for the better have to be encouraged (Barkin, 2006 and United Nations Development Programme, 1994).

1.4.4 Corporate Sustainability

Key institutions of modernity are identified by Beck (2006) as science, business, and politics, which are no longer highly rated as trustees but rather as sources of risk (Beck, 1992) in society. Businesses or corporates in general are also key vehicles for poverty reduction and human development; hence the need for their sustainability amidst prevailing mistrust and new expectations (Sudha, 2007; and Beck, 2006).

Corporate sustainability is a strategy for sustainable development and emphasises the need for a balance between the internal and external environments as well as social and economic factors experienced in the course of business. In terms of the environment, the concept includes aspects of energy use efficiency, inclination towards the use of renewable sources of energy, waste management, environmental management systems, and product life cycle management. Those key factors are achievable through lower emissions, environmental investments, and innovation.

Economic considerations in corporate sustainability focus on the firm's performance, customer satisfaction, and shareholder loyalty. Key economic indicators include safe and good quality products, income generated from operations, revenues, costs, and added value. The social aspect of corporate sustainability involves matters of safety and health, education, human rights, community, and responsibility regarding produced products or those in the process of development and use (Kocmanova & Docekalova, 2011; and Benn, Dumphy & Griffiths, 2006).

Corporate sustainability relies more on perceptions of risk caused by corporates, held by different stakeholders at a particular time and in a given context (Beck, 2006). Lack of corporate sustainability largely perpetuates corporate culpability, manifesting through erosion of trust and flight of the much-needed social license. Corporates, by their nature, provide sought-after solutions for society and societal development. To achieve that, they must use resources whose transformation for usability is sometimes disruptive and poses risks (UNDP, 2015; and World Bank, 2017). Hence, contributing to the destruction of life and life-supporting systems in the process of seeking development and related products and materials.

Corporate sustainability is also central to sustainable development and disaster risk reduction (Uitto & Shaw, 2016). It is central as part of the strategy for poverty reduction when viewed as vulnerability reduction. Yet, it is also central as noted in development discussions, which is usually agreeably disruptive in that it displaces something and emits something in production (UNDP, 2015; and World Bank, 2017).

This realisation calls for testing technology before its rollout to ensure context-specific sustainability as a business model and for continuous innovation toward less harmful technologies for human security (Winther, 2008). Where corporate social responsibility does not align with local expectations, conflicts have been observed between communities and corporates.

This has threatened business continuity and sustainability, as well as other aspects of sustainable development (Kocmanova & Docekalova, 2011; Benn, Dumphy & Griffiths, 2006; and Winther, 2008). Corporates are now judged not only by their services, products, and profits but also by their impacts on social well-being, and local and global impacts (Zhang, Kambhampati, and Morse, 2017).

Corporate social responsibility is at the center of sustainable development and disaster risk reduction, and it is a human rights issue (Bhagwat, 2011). In trying to distinguish between sustainable development and corporate social responsibility, sustainable development is viewed as belonging to the public policy realm.

The Our Common Future Report also influenced corporates' thinking toward responsibility and sustainability (Barkin, 2006; Mitcham, 1995; and United Nations, 1987). Mainstream investors are thus being challenged to review corporate social responsibility issues when analysing companies. They are sometimes required to take these considerations into account, noting that key issues revolve around meeting the needs of poor people in the course of doing business, while also acknowledging limitations of technologies and existing organizations.

Climate change and environmental harm in general have quantifiable economic and health costs that weigh on long-term growth and well-being. Climate change is expected to reduce the world's GDP by around 0.7 to 2.5% by 2060 if it is not addressed, and mitigation would be costly (OECD, 2015). However, The Stern Review argues that the benefits of aggressive, early action on climate change outweigh the costs of inaction (Stern, 2006). The shift to a carbon-neutral global economy, on the other hand, presents attractive opportunities. Climate change can be a lucrative business opportunity for green industries. For example, market research in Paris found that carbon-neutral goods and services could boost France's GDP by 5%, amounting to $10.3 trillion in monetary value (Portala, 2023).

Arguably, corporate social responsibility focuses on individual business organisations, although some are already calling it business statesmanship. Corporate sustainability also deals with organisational level environmental management policy. The use of terms like "sustainability," "sustainable development," and corporate sustainability has been a matter of debate and confusion among scholars and practitioners (Sheehy and Farneti, 2021).

1.4.5 Theoretical Implications to the SD Concept and Study

Coalescence of the three theoretical strands broadens the understanding of the matter under study. Additionally, working with them in unison justifies their inseparability and concordance in practice. The innovation advanced in this study is part of the ongoing work against the threats already facing human security and sustainable development in general, in line with the thinking of Barkin (2006), Wisner et al. (1994; 2003), United Nations Development Programme (1994), and Robert Chambers and Gordon Cornway (1992), among others.

Whereas this study sought to impact a number of Sustainable Development Goals, its relevance is mainly linked to Goal numbers 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 13 (Climate Action), 15 (Life on Land), and 5 (Gender Equality).

1.5 Broad Objective

To critically examine the potential implementation of hydrogen as an energy innovation and accessibility solution for sustainable development.

1.5.1 Sub-Objectives

Sub objectives are to:

- identify the existing global energy mix.
- evaluate existing energy sources and their accessibility gap in Zimbabwe.
- determine the role of hydrogen as an alternate energy vector.
- assess the challenges and opportunities for implementing hydrogen-anchored energy innovation.
- recommend theoretical and practical actions for hydrogen-anchored energy innovation and accessibility solutions.

1.6 Main Study Question

What are the barriers to and opportunities for using hydrogen as an alternate energy vector aimed at sustainable development in Africa?

1.6.1 Sub-Questions

Sub questions are:

- What is the existing global energy mix?
- What are the existing energy sources and their accessibility gap in Zimbabwe?

- What is the role of hydrogen as an alternate energy vector?
- What are the challenges and opportunities for implementing hydrogen-anchored energy innovation?
- Which would be the recommended theoretical and practical actions for hydrogen-anchored energy innovation and accessibility solutions?

1.7 Statement of the Problem

Poverty, climate change, and renewable energy have a huge nexus. First, hydrogen generated through the electrolysis process as an energy source is advanced as having the potential for decarbonising economic activities. Yet, there is still a need to establish consensus on pathways for leveraging its full benefits globally, particularly in developing countries.

Second, green hydrogen is postulated as having the capacity to impact development and improve grid electrical power balancing in national contexts.

Third, there is still a gap in knowledge on the quantification of non-monetised benefits of green hydrogen for developing countries, as well as data on hydrogen production in different countries. Hence, this study.

Fourth, there is a need to understand the potential scale that the green hydrogen market has in developing countries. Fifth, there is an urgent need to assess applications in which green hydrogen can deliver gains. Finally, there is a further need for analysis of drivers that can encourage domestic production versus imports of green hydrogen.

As alluded to above, energy, especially hydrogen, is not yet fully harnessed for development in developing countries. This is despite the potential and existing acknowledgment of its role under the United Nations Sustainable Development Goal No. 7.

Using the case of Mukaratigwa Village, this study aimed to provide socio-cultural and technical insights on energy innovation and accessibility with the potential to complement poverty alleviation and sustainable development efforts in developing countries.

There is an energy supply and accessibility challenge among low to medium-income populations in developing countries. Unless both supply and accessibility gaps in energy security are tackled through innovative solutions, energy security remains a missing link in the poverty reduction and sustainable development discourse in developing countries in Africa.

1.8 Research Methodology

Philosophically, the study was rooted in the pragmatic worldview approach. It is not committed to one philosophical or methodological approach since it seeks to bring about practical innovative solutions to a real-world problem. In this context, pragmatism, as is natural, is paired with a mixed-methods design incorporating both quantitative and qualitative research methods (Grover, 2015).

The study involved secondary (including comparative case studies) and primary research (including existing cases), concurrent and partially sequential qualitative and quantitative data collection procedures (for cross-verification and exploration), and analysis techniques for overall triangulation (Quant and Qual) as recommended in Doyle, Brady, and Byrne (2009) & Creswell (2014).

For data collection, a broadly ethnographic approach employed a closed and open-ended survey questionnaire, key informant interviews, feedback workshops (three), and seminar discussions (two). Existing secondary data from key national energy suppliers and related policy-making institutions were also accessed for analysis. The quantitative data was processed using the Statistical Package for the Social Sciences (SPSS), while qualitative data was processed using thematic analysis.

SOLIDWORKS® 2022 Software was used for developing the electrolyser design, including testing its efficiency. As a result, both qualitative and quantitative data were used to explain one another. Global Solar Atlas v2.7 (June 2022) was also used to profile and simulate the solar energy radiation intensity and size the photovoltaic (PV) array for the Mukaratigwa Village project. Throughout the study, research ethics were adhered to.

1.8.1 The Experimental Part of the Study

The experimental portion of the study was primarily used to answer the third objective of this study. The objective was specifically to experiment on the potential role of hydrogen as an innovative energy solution in a developing country's rural setting. To achieve this objective, the researcher designed and sized the electrolyser for splitting water into hydrogen and oxygen for storage. The hydrogen was to establish the sustainability of efficient production, supply, and storage. The resultant electrolyser was hypothetically applied in the rural community (Mukaratigwa Village) to establish its potential contribution to sustainable human and national development. It was also meant to explore the possibility of production sustainability, market sustainability, and sustainable use accessibility. Table 1.1 presents the materials that were required for the experimental study at a single study site which is Mukaratigwa Village.

Table 1.1: Materials required for the Mukaratigwa Village

Item	**Proposed Quantity**	**Estimated Cost (USD)**
Hydrogen Burners for home cooking and heating	98	4900
Off-Grid Hydrogen Generation Site Establishment (Shurugwi Rural).	1(50m*50m)	7500

Hybrid electric power generation solar photovoltaic panels	125	18750
Electric power alternative source (Wind) for ancillary power	8	2400
Electrolyser 25kW	1	33000
Water source (borehole) and connections	1	5000
Hydrogen tanks	9	4860
Container	2*20ft	4000
Hydrogen storage container (Butyl rubber tank)	2*40ft	14000
Green transport vehicles (three-wheeler scooter/bike)	2	3400

1.8.2 The Constructivist Part of the Study

This section of the study was used to determine societal perceptions of the subject under consideration through qualitative and quantitative critical analysis. Thus, establishing a baseline understanding of energy provisioning behaviors, scoping out attitudes to a new energy technology, and indicating how behavior change interventions could be implemented. Data generated through both qualitative and quantitative data collection tools was used to draw conclusions as they sought to test the set study hypothesis.

The study participants included key organisations involved in energy systems planning and development, generation, and hydrogen energy supply, distribution, and users. Households that were connected to the electrical energy distribution network but without access to it and those that were connected and had access to it were also included. Community leaders and an academic specialised in renewable energy also participated. Table 1.2 below provides a summary of the study population and sample.

Table 1.2: Summary of the study population

Study Area	**No. of HH**	**Sample**	**Average HH Size**
Model Village	98	1 (x98)	5
Key Organisations working with the village		1 (x7)	-
Representatives from Organisations involved in Industrial hydrogen		1 (x12)	
Focus group discussions		2 (x5)	
Community Leaders		1 (x3)	-
Total Participants		**1 (x130)**	**-**

1.9 Ethics

The researcher took note and complied with the requisite ethics to ensure the physical and psychological safety and security of the data of participants. In that respect, the researcher was aware that where equipment and materials were to be deployed, they had to be inspected, and in this case, training of participants for compliance had to be conducted with support from Swansea University.

Requisite compliance with international standards was also prioritised and met, and preparation for final deployment was articulated in Chapter Three. This further applies to a tank farm for liquefaction and storage of some experimental materials. Additionally, principles of research integrity were upheld throughout the study.

1.10 Delimitation

The experiment was situated in one ward (Ward 9) in Mukaratigwa Village, Shurugwi Rural District in the Midlands Province. There are ten (10) provinces in Zimbabwe. The study established the possibility of using hydrogen as an energy innovation and accessibility solution in developing countries.

1.11 Limitations

The main limitation of this study was research funding, which constrained access to more gadgets for site deployment experimentation. One village was selected for experimental research while participants who had knowledge of the village or the subject matter were selected for quantitative and qualitative research respectively. All this was done to strike a balance between financial constraints, and achieving the desired objective of the study.

Deployment of the designed electrolyser was deferred and recommended for further research to allow a full comprehension of the requisite results in the study. This did not negatively impact the overall results of the study. The researcher instead used parameters of the designed electrolyser to search for further data which assisted in closing the gap, including through use of secondary data that facilitated hypothetical application in the study site.

1.12 Study Justification, Policy Relevance, and Key Issues

Key poverty reduction models (Wisner, Blaikie, Connon, and Davis, 1994; and 2003; Chambers and Cornway (1992)) have not made significant progress in their intended purpose, despite influencing many interventions. It was in this view that the researcher regarded energy as having a high potential for real, sustainable development-oriented poverty reduction in developing countries. This potential can be realised if innovative solutions are developed.

If implemented, this study bears the potential to go beyond immediate needs to economic transitioning (job creation, wealth creation, cleaner energy use uptake, and women's empowerment), which are viewed as key to sustainable development. Energy is expected to assist in addressing the plight of girls and women in addition to key vulnerable populations such as the elderly, children, people with disabilities, and the terminally sick.

This study, therefore, tested a view that was found positive and thus challenges existing theoretical, practical, and policy approaches. The thesis advances the application of novel and innovative solutions to the poverty challenge. It also suggests the implementation of more "hard" than "soft" sustainable development-oriented poverty reduction policies, economic transition, and stabilisation policies continuously needed in developing countries.

The study transcended disciplines by incorporating engineering, sociological, business, and economic development perspectives. It was pragmatic; hence it is important for tackling real-life challenges that need real-life solutions beyond silo theoretical advancements.

1.13 Thesis Outline

The thesis outline is presented in Figure 1.1 below.

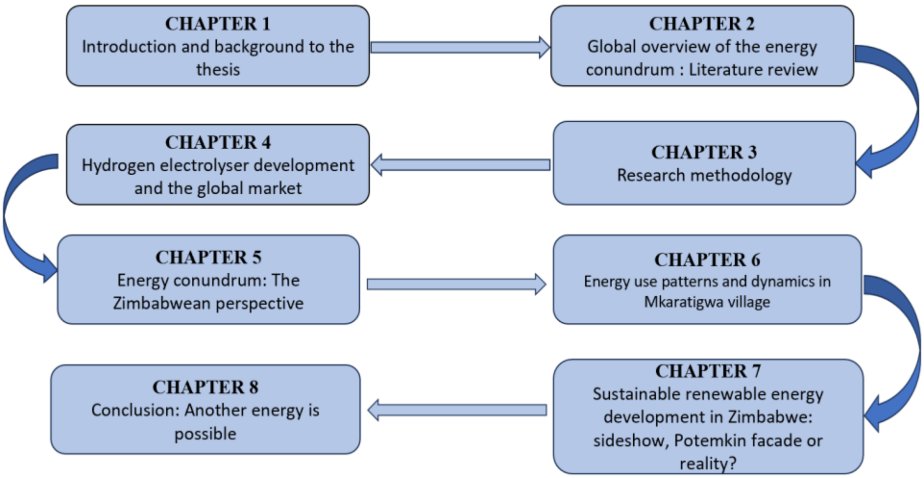


Figure 1.1: Thesis outline overview (Author's Compilation, 2024)

1.14 Chapter Summary

The study is premised on a theoretical framework that amalgamated corporate sustainability, sustainable development, and disaster risk reduction as core mechanisms for poverty alleviation in climate change-risk-threatened communities. It challenges existing approaches in trying to come up with more sustainable solutions to the poverty challenge in developing countries. Renewable energy has been taken as the independent variable because of its futurist role as part of the clean energy technological innovations. Clean energy is even more critical today and into the future in light of the dilemmas posed by fossil primary energy abundance and the advanced need for cleaner energy technologies. The chapter that follows provides a global theoretical overview and progress achieved so far toward the implementation of cleaner energy innovations and to a larger extent green hydrogen, to achieve climate neutrality.

CHAPTER TWO: LITERATURE REVIEW

2.1GLOBAL ENERGY CONUNDRUM

This chapter provides a comprehensive literature review of the current global state and perspectives of the energy sector, with a distinct emphasis on hydrogen technology theory, growth, and potential for adopting hydrogen as a clean energy vector. The chapter begins with a broad overview of the global energy landscape, and then addresses the historical evolution of energy sources and their implications for the overall international energy economic and social structures. As the chapter progresses, it delves deeper into the foundational role of hydrogen in today's energy discourse, the technological advancements facilitating its production and utilization, as well as the challenges facing its widespread adoption. Comparisons with other energy sources, including fossil fuels and renewables, enhanced the understanding of hydrogen's unique position in the global pursuits for sustainable energy solutions.

The chapter further highlights the driving forces behind the shift toward hydrogen in light of the pressing need to mitigate the threats posed by climate change. Further, it is structured to guide the reader through an understanding of energy consumption patterns by sector. The chapter establishes that the rise of hydrogen technologies further guides the socio-economic dimensions that intertwine energy production and usage. Finally, the chapter critically analyses the obstacles that stand in the way of hydrogen commercialisation, along the potential pathways for overcoming these hurdles, followed by offering a roadmap for future innovation, research and development of the technology. Effort applied in reviewing the diverse hydrogen technology theory and the implications of the hydrogen gas classification (colour coding), production, storage, optimisation, commercialisation and use in practice, laid the ground for understanding the current green hydrogen development stage. That provided guidance on key hydrogen production materials and key aspects for consideration in Mukaratigwa Village. Thus, the knowledge was built from the more abstract to the particular, facilitating easy conceptualisation of the technology as a precursor to its application.

2.2. Introduction

This chapter critically examines the developments in the energy sector, centering on green hydrogen as a clean energy vector while juxtaposing it with other energy sources. The urgency to transition towards hydrogen is reinforced by climate change realities, compelling innovations, and the exploration of hydrogen potential across diverse regions. Thus, discussions on other energy sources in this Chapter provide a base for comparative analysis of the status of hydrogen use globally. There is adequate evidence that there is a positive trend in research supporting the use of hydrogen in industries and households due to the many advantages associated with it. Threats posed by climate change to human survival are established as the main drivers of hydrogen innovation. However, despite the concentration of hydrogen technologies and innovations in fewer parts of the globe, distribution of the hydrogen sources is universal. This chapter unpacks the evolution of hydrogen from hydrocarbons to green hydrogen, hydrogen technologies, methods being used, as well as existing challenges and breakthroughs.

In the realm of hydrogen production technologies, various studies have explored the design and application of electrolysis systems with differing capacities tailored for specific energy demands. Notably, as cited in Chapter Three, Wanjiku et al. (2011) provided a foundational analysis of an electrolyser system that was configured for a modest output of 0.8 kW, primarily focusing on Proton Exchange Membrane (PEM) applications. While this research offers valuable insights, it contextualised Wanjiku's findings within the scope of the current study to arrive at a significantly larger 40 kW electrolyser configuration. That 40 kW electrolyser then guided the Mkaratigwa Village baseline study that informed Chapter Six of this thesis. This discrepancy in scale necessitated a reconsideration of the theoretical models derived from Wanjiku's work, particularly regarding energy production calculations and the operational dynamics applicable to a larger electrolyser.

Furthermore, adapting methodologies from a smaller electrolysis stack, such as the one derived from Wanjiku, required careful evaluation to ensure the unique operational and environmental conditions present in rural Zimbabwe were adequately addressed. This study articulated these adjustments and contextualised the relevant calculations to ensure clarity and alignment with the research objectives. By doing so, enhanced the relevance and applicability of existing formulas while establishing a clear connection between the size and operational efficiency in electrolyser design. The methodology section (Chapter Three) of this thesis provides the necessary context regarding the differences in electrolyser capacity between Wanjiku's work and the focus of the current research, helping to clarify the importance of these distinctions and enhancing understanding of the relevance of this methodological approach.

2.3. Evolution of Energy and Energy Use

A geographical understanding can illuminate how regional and national contexts influence energy transitions and utilisation patterns, as well as the socio-economic implications tied to these evolutions.

- **Regional Resource Availability**: The availability of natural resources is uneven across different regions, shaping their energy sources. For example, countries with abundant sunlight, such as those in Southern Europe and parts of Africa, are more likely to harness solar energy (Schwartz et al., 2017). In contrast, nations rich in fossil fuels, like those in the Middle East, continue to rely heavily on oil and natural gas. This geographical context engenders a significant influence on the types of energy sources that are viable and the pace at which countries can transition to alternatives, such as hydrogen (Murray and Holbert, 2014).

- **Economic Development and Energy Access**: Disparities in energy consumption between emerging economies and developed nations are often closely linked to geographical factors. Emerging economies frequently face geographical barriers like inadequate infrastructure and uneven resource distribution, which hinder energy access. In regions like sub-Saharan Africa, where energy infrastructure is underdeveloped, households still depend heavily on traditional fuels, such as wood and dung. This reliance underscores the necessity for energy policies tailored to specific geographical contexts to promote sustainable energy use (Kaseke, 2013; Aliyu et al., 2018).
- **Climate and Environmental Factors**: Geographic diversity also informs how energy systems respond to climate and environmental conditions. Coastal regions may invest more heavily in wind energy due to strong ocean breezes, whereas arid regions might focus on solar energy (Fouquet, 2016). Physical geography also affects vulnerability to climate change and thus influences energy policies; regions susceptible to extreme weather events are likely to prioritize energy systems that are resilient and adaptable (Hinrichs and Kleinbach, 2012).
- **Socio-political Dynamics**: The geographical distribution of energy resources often aligns with socio-political dynamics. Nations abundant in fossil fuels may have limited incentives to innovate in renewable energy sectors due to the economic advantages derived from fossil fuel revenues. This tendency creates a divide where regions rich in fossil fuels may lag in adopting hydrogen technologies (Golubev et al., 2012). Conversely, countries like Germany—despite lacking fossil resources but possessing the geographical capacity for renewable innovation—are at the forefront of hydrogen technology development and policy advocacy (Simandan, 2020).
- **Urban vs. Rural Energy Use**: The contrast between urban and rural areas leads to varying energy use patterns. Urban centers generally have a higher demand for and access to diverse energy forms, such as electricity and modern fuels, while rural areas may still depend on traditional biomass and limited electricity access (Dube et al., 2014). Thus, geographical contexts also shape sectoral energy use, as industries in urban environments tend to transition more rapidly to renewables than rural sectors primarily engaged in agriculture that rely on non-mechanized processes.
- **Global Flow of Energy and Technology**: Additionally, understanding the geographical context involves recognizing the global implications of energy use and evolution. International trade allows some regions to export their energy surplus while importing energy from others, emphasizing the interconnectedness shaped by geography (Tonn et al., 2010). The shift towards hydrogen energy, for example, requires global collaboration and technological exchange influenced by geographical proximity and geopolitical relations.

By and large, examining the geographical influences on energy evolution and use reveals that energy systems are far from homogenous. Local contexts profoundly shape energy accessibility, technology adoption, and sectoral energy use, warranting tailored strategies that consider geographical specifics. This nuanced understanding can inform more equitable and efficient energy policies that leverage local resources while promoting a sustainable transition towards energy systems, such as hydrogen, that address the dual challenges of economic development and environmental stewardship (Malanima, 2021).

Energy is an integral part of societal infrastructure and it influences both national economic growth and the population’s living standards. This section outlines the major transitions in energy sources, with particular focus on hydrogen, which is emerging as a sustainable alternative. The researcher zoomed into the scholarly thinking that energy is a ubiquitous part of modern society and its application is depending on the type of force at work (Murray and Holbert, 2014 and Simandan, 2020). Gleaned literature validates the idea that energy influences every aspect of society from economics and labor to environmental considerations, international relations, personal lives and life-supporting structures such as housing, food, health, transportation and recreational activities (Fouquet, 2016). It is essential for extracting and transforming materials from their natural state into products and services we rely on (Hinrichs and Kleinbach, 2012). However, many developing countries experience significant challenges in energy availability, which impedes progress despite the necessity of energy for development (Tonn et al., 2010; Kaseke, 2013; BEIS, 2018).

Electricity is recognised as the most accessible and consumable form of secondary energy, critical to any economy's long-term viability (Simandan, 2020). Its absence can have severe repercussions for societal functions (Malanima, 2021). Consequently, the availability of electricity is often used as an index for measuring the quality of life in a given country, underscoring the vital role of energy in economic systems (Dube et al., 2014). To contextualise secondary energy as a concept the study borrows from Overgaard (2008) that secondary energy is energy embodied in commodities that come from human induced energy transformation.

Emerging economies, which account for nearly three-quarters of the global population consume only one quarter of the world's total energy production (Golubev et al., 2012). Traditional fuels such as wood, charcoal, animal dung, and crop residues constitute a significant portion of the energy balance in these regions. These are often collected freely by rural households for cooking and heating (Tonn et al., 2010; Kaseke, 2013; Aliyu et al., 2018).

As Table 2.1 illustrates, the timeline of energy discoveries spans significant milestones that have shaped our energy landscape. Notably, the recent push for alternative energy solutions since the 2000s emphasises the gradual transition toward renewable sources, including wind, solar, and hydrogen energy. The increasing focus on hydrogen, particularly as a clean energy carrier, is critical for addressing climate change and in promoting sustainability in energy systems. Innovations and advancements in hydrogen fuel technologies present a vital opportunity to reduce reliance on fossil fuels and enhance energy security. For instance, recent investments in hydrogen infrastructure leverages potential in various sectors including transportation and industry and aligns with global efforts to transition toward low-carbon energy solutions (Schwartz et al., 2017).

Table 2.1: Timeline of Energy Discoveries: An Analogy of Hydrogen Innovation Trajectory

Year	**Event**
Over 10,000 BC	Humans discover how to make fire.
2000 BC	Coal is used for heating and cooking in China.
A.D. 1	Chinese first collected and refined petroleum as a fuel for lamps.
200 A.D.	Europeans build wheels in rivers and streams to harness water as an energy source.
1000 A.D.	Persians build the first windmills as an energy source.
1600s-1700s	The British discovered how to cook coal to transform it into hot-burning coke, which becomes a major fuel for the 18th, 19th, and 20th-century industries.
Early to Mid-1700s	The invention of pumps to remove water from mines makes intensive coal mining possible.
1820s	First natural gas well drilled in Fredonia, New York.
1830s	Electric generators, motors, and relays are developed.
1850s	The first oil well drilled in Titusville, USA.

Year	Event
1860	The first solar generator was built by France's Auguste Mouschout using a mirror to focus sunlight to create steam.
1879	U.S. inventor Thomas Edison invents the carbon filament light bulb.
1880s-1890s	Nikola Tesla invents the alternating current (AC) system of electrical generation, which becomes the standard as nations across the world are wired in the late 19th and 20th centuries.
1892	The first use of geothermal energy to heat buildings.
1948	Discovery of the Ghawar oil field, the world's largest petroleum deposit in Saudi Arabia.
1950	The first nuclear power plants are built in Obninsk, former USSR.
1980s	Scientists begin to amass evidence that the burning of fossil fuels is driving potentially catastrophic global climate change.
2000s	Increased efforts to develop and use alternative energy sources like wind, solar, hydrogen, and geothermal energy.

*(**Source:** Adapted from Godula-Jopek, 2015).*

This evolution not only reflects changes in energy consumption patterns across sectors but also highlights the need for integrated energy strategies that incorporate diverse resources including hydrogen. That assists in meeting future demands effectively across all sectors from residential to industrial, including the primary, secondary, and tertiary sectors.

This section provides a clearer connection between the content and Table 2.1 while explicitly discussing the role of hydrogen as the focus of the study. The analogy of contemporary inventions' relevance to this study's focus on hydrogen innovation helps to integrate it into the broader context of energy evolution and use by sector.

2.3.1. Energy Use in Domestic and Industrial Sectors

By analysing energy consumption in the U.S. and Zimbabwe, the variable roles of energy in residential and commercial sectors are explored. The rising adoption of hydrogen in industrial applications signifies a potential pivot towards cleaner energy solutions. In the context of the United States, energy use manifests prominently across various sectors, significantly influencing both economic performance and environmental sustainability. As one of the largest consumers of energy globally, the U.S. serves as a crucial case study for understanding energy consumption patterns and their implications for energy policies, particularly concerning the transition to alternative energy sources like hydrogen.

Residential energy consumption accounts for a substantial portion of the national energy balance, driven primarily by heating, cooling, lighting and appliances (EIA, 2021). The integration of more efficient technologies and renewable sources, such as solar and wind, has gained momentum in recent years as households seek to reduce costs and environmental impact. These trends provide essential insights into how energy efficiency measures can be scaled up in other contexts, especially for developing countries, to improve access to reliable energy while minimising greenhouse gas emissions (U.S. DOE, 2020).

In the commercial sector, energy use reflects the operational needs of businesses, including the demand for electricity and heating. Large retailers and office buildings are leading the charge toward sustainability, often implementing initiatives such as energy-efficient lighting and HVAC systems, as well as actively exploring solar energy installations (U.S. DOE, 2020). Understanding the commercial sector's practices provided relevant lessons for enhancing energy use in similar sectors worldwide, emphasising the economic viability of transitioning toward cleaner energy.

The industrial sector represents the largest share of energy consumption in the U.S., utilising vast amounts of energy for manufacturing processes (EIA, 2021). However, numerous industries are increasingly recognising the necessity of adopting practices that promote energy efficiency and sustainability. The focus on hydrogen as a versatile energy carrier is particularly significant. Industries such as steel and chemicals are exploring hydrogen for decarbonisation, showcasing its potential not only as a new energy source but also as a critical component in achieving emissions reduction targets. This insight is particularly relevant for countries undergoing industrial transformation and seeking to align economic growth with environmental goals.

Energy use in mining and agriculture further highlights the diverse applications of energy across sectors. In mining, operations require significant energy input for extraction and processing, raising important considerations regarding energy sources and sustainable practices (Schwartz et al., 2017). Meanwhile, the agricultural sector increasingly depends on energy for activities such as irrigation, production, and distribution. Innovations like precision agriculture and renewable energy integration can enhance efficiency and reduce reliance on fossil fuels, thereby offering useful strategies for other nations aiming to modernise their agricultural frameworks sustainably.

The examination of energy use in the U.S. across various sectors provides insight into best practices, emerging technologies, and sustainable strategies that can be adapted and implemented in different contexts. The focus on transitioning to cleaner energy sources, including hydrogen, aligns with the overarching goals of this study, which seeks to analyse energy's evolving role in contemporary economies and its implications for global sustainability.

The global benchmarking enhances the relevance of U.S. energy use to the study by drawing connections to broader themes of sustainability, energy efficiency, and the transition toward alternative energy sources, particularly hydrogen. This contextualisation helps meet the research's scope without compromise while enriching the content's quality.

2.3.2. Energy Independence, Quality, Equality and Equity

This section discusses the socio-political implications of energy access. The focus shifts to hydrogen's role in fostering energy independence while ensuring equitable energy access for marginalized communities. Energy independence, quality, equality, and equity are foundational concepts in the fields of energy and sustainability studies, particularly as they relate to the integration of hydrogen as a clean energy source. These concepts inform not only the ethical and social dimensions of energy distribution but also illuminate hydrogen's transformative potential in fostering sustainable energy systems. This research adopts the definition of quality as posited by Rahman, (2024) that quality is an expectation that a product or service satisfies, otherwise the targeted population or customers will be dissatisfied or stop buying a product if they discover the quality has decreased. On the other hand, Equity is fair treatment, opportunity, and advancement for all people while at the same time striving to identify and eliminate barriers that have prevented the full participation of some groups (Minow, 2021). Equality is a fundamental human right, essential for creating a just and fair society that encompasses:

- Social Equality: equal opportunities, rights, and treatment for all individuals;
- Economic Equality: equal access to resources, wealth, and economic opportunities;
- Political Equality: equal participation, representation, and decision-making power;
- Gender Equality: equal rights, opportunities, and treatment for women and men, and;
- Racial Equality: equal treatment and opportunities regardless of race or ethnicity.

As Counts (2022) articulates, "energy independence" is often framed as a political idea wherein countries seek reduced reliance on global energy markets. However, with localised hydrogen production capabilities, energy independence becomes more feasible, allowing nations to diversify their energy portfolios and enhance resilience against fluctuations in global energy markets.

The promise of hydrogen as a versatile energy carrier is pivotal in shaping both national and international climate and energy strategies, particularly in addressing regional inequities (Sovacool, Heffron, McCauley, and Goldthau, 2016). Access to hydrogen resources and technologies will vary significantly across diverse socio-political and economic landscapes, necessitating tailored approaches that consider local contexts. By democratising access to hydrogen technologies, we can create pathways that not only enhance energy quality but also promote social equity.

Democratisation refers to the process of making political systems and decision-making more inclusive, participatory, and representative of diverse interests within society. In the context of energy, democratisation can be understood as empowering communities, especially marginalised groups, to actively participate in energy governance and the development of hydrogen projects. This citizen engagement is crucial for ensuring that energy transitions consider local needs, perspectives, and historical injustices. The democratisation of hydrogen production and distribution can mitigate the risk of exacerbating existing inequalities, ensuring that all societal segments benefit from advancements in hydrogen technologies.

Libertarianism and egalitarianism present differing approaches to transitioning toward hydrogen as an energy source. Proponents of libertarianism advocate for competitive energy markets that encourage innovation in hydrogen production and utilisation (Cochrane, 2022). In this view, privatisation and deregulation can motivate advancements in hydrogen technologies, promote cost reductions, and enhance efficiency. Conversely, egalitarianism raises concerns that a free-market approach may unintentionally deepen existing inequalities, particularly if access to hydrogen technologies skews towards wealthier communities or regions. Thus, ensuring equity in the hydrogen sector requires deliberate policy interventions and inclusive governance structures.

Both of these philosophical frameworks intersect with the notion of democratisation in energy systems. Effective governance structures that prioritise transparency, inclusivity, and accountability are essential for fostering equitable hydrogen access. Addressing historical injustices related to energy infrastructure is critical to breaking cycles of environmental degradation and social inequity. The emphasis on a multidimensional approach, highlighted by Counts (2022), that incorporates various methods including libertarian energy decentralism and democratic energy decentralisation is necessary for establishing a hydrogen-fueled economy that promotes equal access and participation.

Quality, equality, and equity in the context of hydrogen are essential for understanding its role in future energy systems. Quality pertains to the reliability and efficiency of hydrogen technologies, which can vary based on the scale and methods of production and distribution. Equality denotes the uniform distribution of hydrogen resources, ensuring that communities have equal access to this energy source regardless of socio-economic status. In contrast, equity emphasises fairness in how hydrogen's benefits and challenges are shared, highlighting the imperative that marginalised communities have a voice in decision-making processes related to hydrogen energy projects (Adams and Luchsinger, 2009).

As hydrogen technologies advance, it is vital to anticipate and mitigate potential disparities that may arise from the transition. Historical energy transitions have often led to significant socio-economic impacts. For instance, the decline of the coal industry in Germany resulted in substantial job losses, particularly in regions like the Ruhr (Dahibech and Gartner, 2021). Similar challenges can emerge in other sectors as fossil fuel reliance wanes, emphasising the need for supportive policies to address local economic implications and ensure that affected communities are not overlooked.

The European Commission's Just Transition Mechanism exemplifies efforts to ensure that investments in hydrogen infrastructure do not exacerbate existing inequalities. This initiative aims to mobilise resources for regions and communities most affected by the transition, reinforcing the necessity of integrating equity into climate and energy strategies (Strambo, 2020). These views buttress the need to implement green hydrogen research, innovation, development and deployment in the Global South to complement strides already being made in the Global North cognisant that to date. African countries, for instance, have been outspoken against continued exploitation and perpetuation of the Dependency Theory ideas following the African Renaissance.

Therefore, hydrogen has the potential to redefine approaches to energy independence, quality, equality, and equity within the global energy landscape. However, realising a hydrogen-based economy will not rely solely on technological advancements; it will also hinge on the social relations, governance structures, and ethical considerations that influence energy policy. By acknowledging these critical factors, we can work toward a future where hydrogen not only contributes to environmental sustainability but also promotes social justice and equitable economic opportunities for all members of society.

In this study, the concept of democratisation is clearly defined and integrated into the discussion surrounding hydrogen's potential, enriching the context and aligning the section more closely with the overarching focus of the research. This clarity helps to establish a connection between democratic principles and the equitable deployment of hydrogen technologies, emphasising the importance of inclusive governance in achieving sustainable energy outcomes.

2.3.3. Energy Trends in Zimbabwe

A stark contrast exists between energy consumption in the U.S. and Zimbabwe. The latter's energy landscape necessitates transitioning towards hydrogen technologies to revitalize its industrial sector amidst declining energy availability. The industrial sector in the United States accounts for approximately

26% of total electricity consumption (Schwartz et al., 2017). This sector is diverse, comprising small, medium, large, and very large facilities categorized into broad areas, including manufacturing, mining, construction, and agriculture. In Zimbabwe, however, the electricity consumption dynamics illustrate a stark contrast. According to Hosier (1988), electricity consumption across various economic sectors such as agriculture and forestry, manufacturing, mining, transport, and households was recorded at 8%, 49%, 18%, 0%, and 25%, respectively. Notably, this indicates that the industrial sector accounted for a significant 75% of total energy use in the country at that time, positioning it as a dominant consumer of electricity.

Over the years, however, there has been a notable shift in Zimbabwe's energy consumption patterns. By 2011, Chipumho (2011) reported that households began consuming more electricity than the industrial sectors, a change attributed to a sharp decline in industrial production capacities. Recent statistics from IRENA (2022) validate this trend, revealing that by that time, household electricity consumption surged to 90% of the total, while industrial use plummeted to a mere 4%, with the transport sector at 1% and other services at 6%.

The classification of energy use within the industrial sector can be further refined into six critical categories: petroleum refining, steel production, aluminum manufacturing, paper production, chemicals, and cement manufacturing (Foster et al., 2009). Each of these categories has unique energy demands. For instance, petroleum refining entails substantial energy for converting crude oil into various fuels and other by-products. Similarly, steelmaking is energy-intensive due to the high temperatures required for smelting iron ore while the aluminum production process, particularly via Hall-Héroult electrolysis, also demands significant energy (Barron, 2020b). The paper production industry consumes energy at various stages, including chopping and boiling wood into pulp, leading to substantial overall energy consumption. Notably, the chemical industry stands out as the largest energy consumer in this sector, primarily relying on coal, oil, and natural gas to streamline manufacturing processes. Cement manufacturing also involves considerable energy, as limestone and other materials must be thermally processed at up to 1450 °C (Schwartz et al., 2017; Alnawfleh et al., 2015; Barron, 2020a).

In the context of Zimbabwe, such energy demand assessments raise pertinent questions about energy policy and resource allocation opportunities for hydrogen as an alternative energy source. Given the decline in industrial electricity consumption, there lies the potential for hydrogen technologies to revitalise the industrial sector while addressing broader climate goals.

On the other hand, the transportation sector, categorised separately in the broader industrial context, is crucial for moving people and goods via ground, air, and water, primarily relying on fossil-fueled combustion engines. Infrastructure, such as highways, railways, airports, and marine docks, forms the backbone of effective transportation systems. Two major categories of transportation exist: passenger and freight. In the United States, the transportation sector utilises less than 1% of total electricity per year (Schwartz et al., 2017). Taking note of the presence of over 200 million vehicles, only about 270,000 are electric or hybrid models, highlighting a reliance on traditional combustion engines and contributing to fossil fuel consumption.

Zimbabwe's transportation context is fraught with challenges, given the country’s energy crisis and low electricity reserves (Bergasse, 2013; Kaseke, 2013). Rising fuel costs directly correlate with struggles to attain climate and energy supply goals, where higher fuel prices exacerbate economic pressures on consumers. However, this situation does not contradict the objective of addressing climate change; rather, it underscores the urgent need for transitions to cleaner energy sources, including hydrogen. As fossil fuel reliance persists, the potential for hydrogen to serve as a clean alternative in the transportation sector becomes increasingly relevant, promising to reduce emissions and dependence on finite resources.

The hydrogen market is expected to develop over the coming years thanks to penetration in sectors where an immediate shift to electrification will be difficult or not feasible. As discussed above, industries such as steel, chemicals, and cement manufacturing represent industrial segments where the use of hydrogen offers low switching costs by decarbonising the fuel used in the manufacturing processes without the need for significant technical or logistical redesigns. Heavy transport (such as ships, trains, trucks, and forklifts) presents an additional opportunity for hydrogen owing to the relatively high cost and impracticality of alternatives such as large-scale electricity and battery storage infrastructure. Hydrogen blending in the European pipeline network has the potential to have an impact on both industrial and domestic usage and also to open up opportunities (such as heating) for transformation in the residential sector (Corbetti et. al., 2024).

2.3.4. Global Energy Crisis and Possible Solutions

The ongoing global energy crisis illustrates the unsustainable reliance on fossil fuels. Integration of advanced hydrogen technologies presents a viable route to address energy shortages while aligning with environmental sustainability goals. The global energy crisis results from a combination of factors, including population growth, increased energy consumption across developed and developing regions, and ongoing reliance on fossil fuels for energy generation and transportation (Coyle and Simmons, 2014). Compounding these challenges is that approximately 2 billion people lack access to modern energy services (Foster et al., 2009). Energy represents the cornerstone of contemporary living, making the challenge of energy poverty a top global priority critical to combating extreme poverty (Mapira and Munthali, 2011).

Countries like China and India are already grappling with energy shortages amid an unsettling paradox: as fuel costs escalate in areas where it is scarce, the impacts of global climate change are simultaneously worsening. This correlation is not inherently contradictory. It rather, reflects the reality that fossil fuel consumption contributes to climate change and economic pressures. The adverse outcomes of energy consumption extend to health and safety, manifesting in shifts in weather patterns and deteriorating air quality (Greenstone, He, and Lee, 2022).

The disparities between current energy use and human expectations contribute significantly to the challenges associated with the global energy crisis (Murray and Holbert, 2014). Concerns about carbon emissions are compounded by anxiety surrounding the availability of crude oil globally, in the face of rising market demand. Notably, conventional crude oil production has stagnated since 2005, failing to meet escalated demand (Murray and King, 2012). Before this point, oil production adequately responded to demand. Since then, supply stability has waned (Coyle and Simmons, 2014).

In Africa, growing energy demand reflects rapid population growth and the historical lag in economic transition. Despite possessing diverse renewable and non-renewable energy sources, the continent remains heavily reliant on oil, gas, and traditional biomass, leading to significant social, economic, and environmental constraints. The energy crisis in many African nations, including Zimbabwe, is exacerbated by dwindling electricity reserves. Electricity reserves are the energy that remains available after meeting all consumer demands (Pretorius et al., 2015). With an already low electricity supply, Zimbabwe faces urgent challenges concerning energy sustainability. The integration of innovative solutions such as hydrogen should therefore enhance energy resilience. This study emphasises enhancing and aligning the energy mix and usage across all sectors to the overarching focus on hydrogen potential within the Zimbabwean context. The narrative now ties the importance of hydrogen technologies more evidently into the current discussions related to industrial and transportation sectors, as well as the broader implications for addressing the energy crisis.

2.4. Energy and Social Issues

This section delves into the interconnectedness of energy use and social challenges. It emphasises how clean energy solutions like hydrogen can mitigate energy poverty, thus, fostering socio-economic progress.

Many socioeconomic challenges, such as poverty, population growth, urbanisation, limited opportunities, and gender disparities, are inherently linked to energy use (Asghar, 2008; Winther, 2008; Stern, 2010; Bergasse, 2013; Lloyd, 2017; McCollum et al., 2017). These factors not only drive energy demand but are fundamentally interconnected in two key dimensions. First, the availability and quality of energy services, along with the mechanisms of their delivery, represent broader societal structural issues. In emerging countries, where poverty remains a dominant concern, the use of traditional fuels keeps people impoverished, while accessibility to reliable energy can significantly influence economic and social progress.

The statement "the use of traditional fuels keeps people impoverished" refers to the idea that reliance on traditional fuels, such as firewood, charcoal, and dung, perpetuates poverty in several ways:

- ***Financial Burden:*** Spending a significant portion of household income on fuel for cooking and heating can strain finances, leaving limited resources for other essential needs.
- ***Health Impacts:*** Burning traditional fuels indoors releases harmful pollutants, causing respiratory issues and other health problems. This can lead to increased medical expenses and lost productivity.
- ***Time-Consuming:*** Gathering and processing traditional fuels requires significant time and effort, which is often taken away from more productive activities, education, or personal development.
- ***Limited Economic Opportunities:*** Reliance on traditional fuels hinders economic growth by:
    - Limiting access to modern energy services for entrepreneurship and income generation.
    - Perpetuating low-productivity agriculture and manual labor.
- ***Environmental Degradation:*** Over-reliance on traditional fuels contributes to deforestation, land degradation, and climate change, threatening long-term livelihoods.
- ***Lack of Access to Education:*** Children, especially girls, may be forced to spend time collecting fuel instead of attending school.
- ***Increased Vulnerability:*** Dependence on traditional fuels makes households vulnerable to price fluctuations, supply disruptions, and natural disasters.

Individuals in impoverished communities often depend heavily on traditional fuels such as firewood (heating and cooking) and kerosene (lighting) for their energy needs. This reliance perpetuates a cycle of poverty, as these energy sources are inefficient and unsafe. Traditional fuels used for cooking and heating often do not provide sufficient energy for lighting homes, hindering educational opportunities for children who need to study from dusk. Moreover, these energy sources require significant time and labor to gather and prepare, diverting women and children from education and productive activities, which is often referred to as the "time tax" of energy poverty. Energy poverty is a significant issue that affects many people around the world.

Globally, over two billion people lack access to electricity, while an equivalent number rely on traditional solid fuels for cooking and heating. Hundreds of millions, predominantly women and children, spend countless hours each day collecting firewood and fetching water for domestic use. This significant time investment in energy-related tasks directly detracts from opportunities for education and skill development, exacerbating gender inequality and contributing to food and health insecurity (Foster et al., 2009; Mapira and Munthali, 2011; Coyle and Simmons, 2014).

Africa's resource wealth starkly contrasts with its limited energy reserves, as the continent has the lowest overall energy capacity globally (Statistical Review of World Energy, 2021). The discrepancy is not merely a byproduct of contemporary dynamics but rather a legacy of colonial policies that prioritised extraction and appropriation over equitable development. The structures and inequities established during colonialism persist, creating profound social imbalances that hinder sustainable development. Historical evidence suggests that investment in energy infrastructure has been inconsistent and largely focused on benefiting external entities rather than addressing local needs (The United Nations, 2019 and Frank, 1979). This perspective suggests that colonial powers exploited resource-rich regions, creating an uneven distribution of wealth and energy access. The forms of colonial exploitation are as follows:

- Extraction of natural resources without fair compensation or benefits to local populations.
- Infrastructure development prioritising colonial interests over local needs.
- Imposition of foreign economic systems, disrupting traditional economies.
- Creation of artificial borders, dividing resource-rich regions.

These colonial exploitations left permanent imprints whose implications will be felt for many generations. The effects of colonialism continue to be perpetuated and are visible through:

- ***Economic inequality:*** Unequal distribution of wealth and resources.
- ***Energy poverty:*** Limited access to modern energy services.
- ***Environmental degradation:*** Unregulated resource extraction.
- ***Political instability:*** Conflict over resource control.

Examples of some colonial injustices experienced in Africa are provided below:

- The Democratic Republic of Congo's cobalt and copper wealth, exploited by colonial powers, now fuels global technology.
- Nigeria's oil reserves, managed by foreign corporations, have not alleviated local poverty.
- South Africa's apartheid regime, supported by colonial powers, perpetuated inequality.

This argument highlights the historical roots of global inequality, emphasizing the need for:

- Resource sovereignty

- Fair compensation for resource extraction
- Local-led development initiatives
- Global economic reforms

By acknowledging colonialism's role in shaping resource and energy imbalances, we can work toward a more equitable distribution of wealth and sustainable development (Amin, 1974 and Rodney, 1972).

In this context, the transition to alternative energy sources such as hydrogen could provide new opportunities for addressing inequities, fostering economic growth, and improving quality of life. Transitioning to modern, sustainable energy solutions can help break the stubborn cycle of poverty by:

- Reducing household expenses
- Improving health outcomes
- Increasing productivity and economic opportunities
- Enhancing education and social development
- Mitigating environmental degradation

The thrust of this study is emphatic on embracing hydrogen potential to augment and compliment other examples of alternative energy solutions that include:

- Solar energy
- Biogas
- LPG (Liquefied Petroleum Gas)
- Electricity
- Ethanol
- Biodiesel
- Hydroelectric power

Communities' pursuit of hydrogen and adoption of modern energy solutions can enable them to break free from the constraints of traditional fuels and move towards a more prosperous and sustainable future.

2.5. Energy and Women

The gendered dynamics of energy access necessitate gender-sensitive energy policies. Integrating hydrogen technologies has the potential to alleviate burdens primarily on women in low-energy contexts.

The intersection between women, gender, and energy has ascended to the forefront of the international development agenda. Interventions that integrate gender considerations into energy policies are increasingly recognised as crucial pathways for achieving the United Nations Sustainable Development Goals (Asghar, 2008; Stern, 2010; Bergasse, 2013; UNDP, 2015; Lloyd, 2017; McCollum et al., 2017;

World Bank, 2017). Key goals include enhancing women's education and employment, improving maternal health, reducing child mortality, increasing access to income, and combating hunger.

Women are intrinsically linked to energy use in various ways, with over 400 million of them relying on non-market energy sources for domestic tasks and economic activities (Coyle and Simmons, 2014). Traditional gender roles often assign domestic responsibilities such as cooking, cleaning, fuel and water collection, childcare, and gardening, predominantly to women (Winther, 2008; Carbonnier and Grinevald, 2011; ESMAP, 2020; Agere, 2021). In times of scarcity or rising energy costs, women disproportionately experience the stress of energy shortages, often operating under physically demanding conditions that contribute to longer working hours and adverse health outcomes.

The health impact of energy poverty on women is multifaceted. Indoor air pollution from biomass fuel use has been consistently identified as a significant health risk, contributing to respiratory illnesses and other health complications (Tonn et al., 2010; Kaseke, 2013; BEIS, 2018). Moreover, the physical labour associated with collecting firewood poses risks such as cuts, falls, and musculoskeletal injuries. A lack of accessible energy sources can also force families to alter their dietary choices, often resorting to raw or minimally cooked foods, which can negatively impact nutritional health, especially in infants. Figure 2.1 illustrates the central role women play as primary producers of biofuel globally, emphasising their contributions while also highlighting the burdens they carry in energy production and consumption.

In light of these challenges, it is the researcher’s view that the potential of hydrogen as a clean and accessible energy source presents an opportunity for transformative change. The study reveals that by facilitating equitable access to energy, particularly in rural and underserved areas, hydrogen technologies could significantly alleviate some gendered energy burdens faced by women. It also promotes economic empowerment and better health outcomes (Corbetti, 2024). This study underscores the essence of elaborating on the connections between traditional fuel use and poverty, clarifying how colonial policies have shaped current social imbalances, and reiterating the "time tax" that keeps people impoverished. Furthermore, it integrates the importance of hydrogen potential throughout these discussions, highlighting how it can contribute to addressing systemic issues faced by women and marginalised communities as shown in Figure 2.1.

Figure 2.1: Women are the primary producers of biofuel worldwide

2.6. Energy and the Environment

Hydrogen's environmental advantages position it as a solution to combat climate change. The environmental impacts of traditional energy systems further underscore the need for sustainable alternatives.

The relationship between energy use and environmental health has become increasingly recognised, with a growing understanding of the detrimental impacts of human activities on the natural world and, consequently, human well-being (National Academy of Sciences, 2020). Anthropogenic factors, including changes in land and water use, industrial emissions, and reliance on traditional energy sources, have led to the pollution of air and water resources and contributed to the irreversible loss of biodiversity. Scientific consensus points to human-caused greenhouse gas emissions as a significant driver of climate change, further underscoring the urgent need for cleaner energy alternatives (Hinrichs and Kleinbach, 2012).

In developing regions, the limited availability of cleaner energy sources exacerbates environmental degradation and poses grave health risks, particularly for women and children who bear the brunt of this burden (Tonn et al., 2010; Kaseke, 2013; BEIS, 2018). The prevailing reliance on inefficient energy sources, such as firewood or kerosene, for household energy needs contributes to indoor air pollution but and the depletion of natural resources, particularly water. As environmental conditions worsen, women are further pressured into time-consuming tasks such as gathering firewood, limiting their opportunities for education and economic participation. This "time tax" is a significant barrier to local development and perpetuates socioeconomic challenges, making it imperative to provide greater access to clean energy alternatives (Goldemberg, 2001).

Efforts to secure cleaner energy supplies are vital for economic stability in developing regions (Carbonnier and Grinevald, 2011; ESMAP, 2020). Despite notable strides in women's literacy and involvement in economic activities, the persistent demands of household energy tasks hinder progress in gender equality. The adoption of higher-quality and more efficient cooking fuels can yield significant improvements, not only in health outcomes but also by freeing up time for women to pursue education and enter the workforce, unlocking their potential and contributing more broadly to societal advancement (Goldemberg, 2001). Thus, transitioning to sustainable energy sources, including hydrogen technologies, presents a crucial opportunity to mitigate these environmental challenges while promoting economic empowerment. By facilitating access to cleaner energy, hydrogen can help bridge the gap between energy availability and environmental sustainability, ultimately fostering resilience in developing communities.

2.7. Historical Context of Fossil Fuels

A historical chronology of energy illustrates the dependence on fossil fuels for energy. The continued exploration of hydrogen as a superior alternative emphasizes the need for a transition toward sustainability.

Historically, wood, coal, oil, and natural gas served as the primary fuel sources. Over the past century, coal, oil, and natural gas have dominated the energy landscape in the industrialised world while still holding sway in many developing nations. In Africa, fossil fuels primarily power high-income households and energy-intensive industries, with kerosene previously serving as a crucial energy source for poorer rural and urban households for lighting (Karekezi and Kithyoma, 2003). However, this reliance on kerosene has diminished significantly in rural Zimbabwe, where households increasingly embrace solar lamps and other renewable sources.

2.7.1. Coal

Coal has been harnessed as an energy source for millennia. Its use dates back to around 1000 BC in China (Tabak, 2009a). It was pivotal in developing steam technology, driving innovations such as the steam-powered pump, and facilitating industrial growth. By the mid-19th century, regions such as Wales began to exploit coal for industrial purposes, establishing the foundation for countries like Britain, Germany, and Japan to emerge as early industrialised nations reliant on coal (Archifau Cymru Archives Wales, 2023). Despite efforts to transition away from coal, it remains a major component of the global energy landscape, contributing to over 40% of worldwide electricity generation (BP Statistical Review of World Energy, 2021).

In Africa, reliance on coal for electricity generation poses significant challenges, particularly for countries such as Botswana, which depend heavily on local coal deposits (African Climate Policy Centre, 2011). While coal can provide essential baseload power for thermal energy conversion, the environmental toll associated with its extraction and combustion is profound. Among the most critical issues is acid mine drainage, often resulting from exposed iron sulfide in coal deposits, which can severely contaminate local water sources. Moreover, the health hazards associated with coal mining, such as black lung disease, underscore the human cost of this energy source (Tabak, 2009a).

While acknowledging coal's historical significance, it is imperative to consider the transition to cleaner alternatives such as hydrogen to support sustainable development goals. The integration of hydrogen as an energy source presents an opportunity to reduce reliance on coal and mitigate its environmental impacts. In this chapter, the author strives to address sustainability aspects by enhancing the discussion of the potential of hydrogen as a transformative energy source. The text now weaves in critical commentary on environmental impacts and historical energy use, emphasizing the need to shift toward sustainable energy solutions. Figure 2.2 illustrates the world's largest coal exporters in 2019, providing context for global coal markets and the ongoing reliance on this fossil fuel emphasising the thrust on hydrogen innovations.

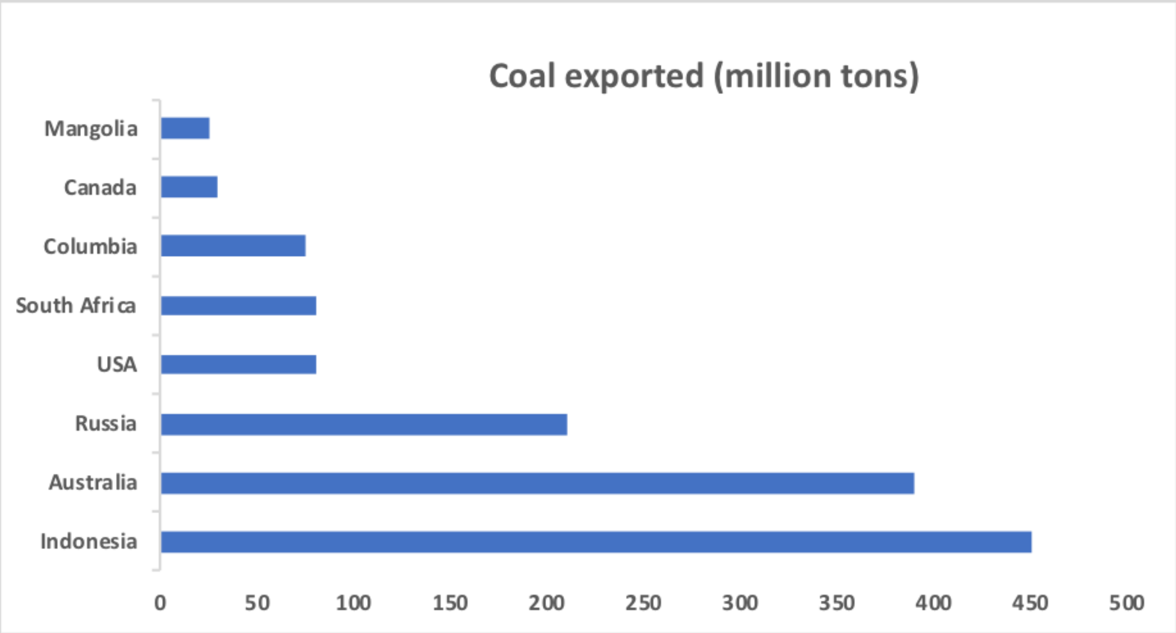


Figure 2.2: Summary of the coal exported (million tons) from the world's biggest exporters (Source: BP Statistical Review of World Energy, 2021)

2.7.2. Oil

The history of oil dates back to around the 4th century AD, when early methods for extracting oil were utilised in China using bamboo poles. This dark, viscous substance served as a valuable fuel source. The modern oil industry began in earnest with Colonel Edwin Drake's successful drilling of the first commercial oil well in Titusville, Pennsylvania, on August 27, 1859, at a depth of just 21 meters (Tabak, 2009a). John D. Rockefeller established an influential oil refinery in 1863 that facilitated the transformation of crude oil into useful products, including kerosene for heating, gasoline for automobiles, and diesel for engines. As the invention of the gasoline engine by Siegfried Marcus in 1875 heralded a new era of transportation, the burgeoning automobile industry further increased gasoline demand. By 1915, gasoline production had overtaken that of kerosene, reflecting a significant shift in fuel preferences.

This trend is palpable in Zimbabwe as households increasingly opt for more sustainable and efficient energy sources, moving away from kerosene(Zimbabwe Energy Regulatory Authority, 2020; Banda, 2016).

The oil crisis of 1973 marked a critical moment in global energy politics, as geopolitical tensions in the Middle East led to OPEC's unprecedented decision to cut off oil supplies and raise prices by 70%. Such volatility in oil markets underscores the fragility of supply chains in politically sensitive regions, perpetuating economic and political turmoil as countries vie for dwindling resources (Sovacool et al., 2016; High and Smith, 2019). This volatile dynamic leads to dramatic price fluctuations, as witnessed during the early months of the COVID-19 pandemic. Countries like Saudi Arabia, Nigeria, Mexico, and Venezuela are significant oil producers. However, the United States remains the world's leading oil producer (Figure 2.3). The Persian Gulf contains a high concentration of proven and potential oil resources, emphasising the region's strategic importance in the global oil trade. Until viable substitutes emerge, the reliance on oil will likely continue driving geopolitical tension and economic instability.

Despite its longstanding role as a primary transportation and heating fuel, oil production is fraught with environmental risks. Pipeline leaks, such as the catastrophic incident in Usinsk, Russia, in 1994, exemplify the potential for disastrous environmental degradation, with an estimated 100,000 to 120,000 tons of oil spilling into the ecosystem (Xia and Boufadel, 2010). Moreover, oil spills like Deepwater Horizon (2010), the Gulf War (1991), and Exxon Valdez (1989) inflict severe ecological damage and threaten wildlife. The financial burden of cleaning up such disasters often exceeds a billion dollars (United States Environmental Protection Agency, 1999).

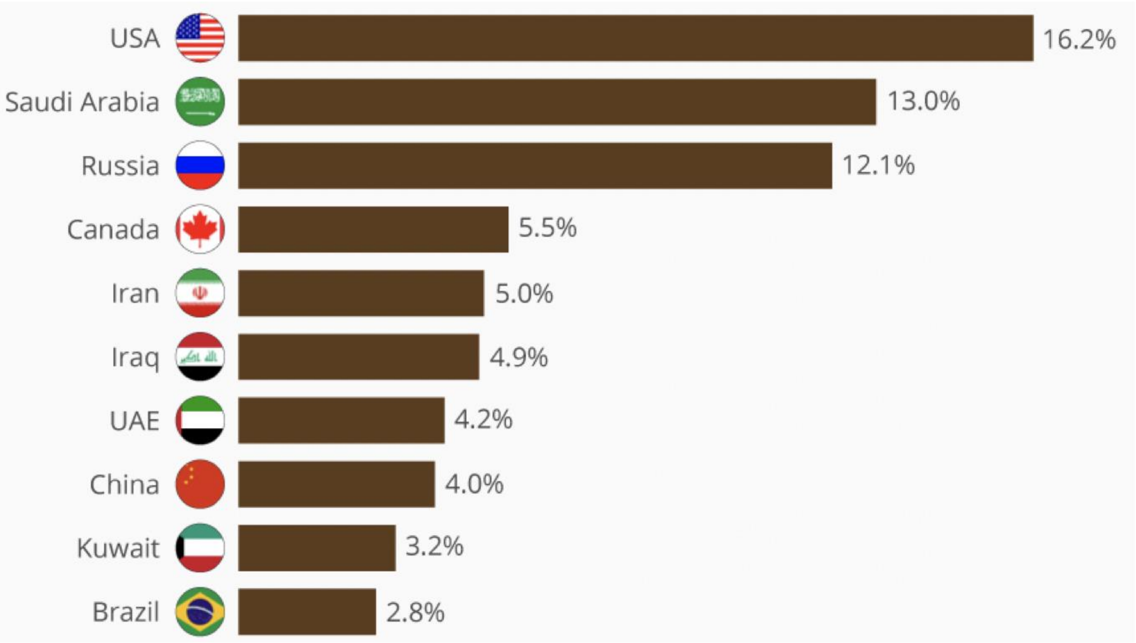


Figure 2.3: Share of global oil production in 2018, including crude oil, shale oil, oil sands, and natural gas liquids (Source: BP Statistical Review of World Energy, 2021).

Oil has long been a transportation and heating fuel while it has also been used in producing diesel, jet fuel, propane, chemicals, synthetic rubber, and other household goods. Conversely, oil production has several drawbacks closely tied to environmental degradation (Goldemberg, 2001). When ferrying oil, there are obstacles such as pipeline leaks. For example, the one experienced in the case of Usinsk, Russia, in 1994 happened when oil leaked from a pipeline housed within a collapsed dike. 100,000 to 120,000 tons of oil leaked, polluting the environment. Oil spills around the world, such as in the Deepwater Horizon in 2010, during the Gulf War (1991), as well as the Exxon Valdez ship disaster (1989), had environmental consequences. Large amounts of oil were spilled onto the surface, killing wildlife and disrupting the ecosystem (Xia and Boufadel, 2010). Cleaning up these spills is expensive, costing over a billion dollars in the USA. Oil refineries have a negative environmental impact as well because they emit large amounts of pollutants into the atmosphere (United States Environmental Protection Agency, 1999).

2.7.3. Nuclear Energy

There is a distinction between early philosophical ideas about atoms in ancient Greece and the later scientific advancements that led to modern nuclear energy. Although early philosophical concepts of atoms emerged in ancient Greece around 2,400 years ago, the contemporary understanding of nuclear energy is a more recent development, beginning with critical scientific discoveries in the 20th century. James Chadwick's identification of the neutron in 1932 marked a pivotal moment in nuclear physics, laying the groundwork for manipulating atomic structures. The first controlled nuclear fission reaction, achieved in 1942, heralded the beginning of the modern nuclear era, spurring significant advancements in nuclear reactor technology (Tousif and Taslim, 2011). In the mid-1930s, as scientific inquiry progressed, some researchers expressed concerns regarding the potential to split heavy atoms or induce fusion. The initial nuclear reactor, constructed in Chicago in 1942, generated a modest 200 watts of electricity. Despite its non-polluting nature, nuclear energy production introduces various risks, particularly in manufacturing processes and radioactive waste disposal. The three primary sources of nuclear energy include fusion, fission, and radioactive decay (Tousif and Taslim, 2011). Thus, while the seeds of the atomic theory were planted in ancient Greece, realising atomic energy and its applications is a comparatively modern achievement that has transformed approaches to energy generation.

Countries such as the USA, Russia, China, India, South Korea, and South Africa generate nuclear energy (Figure 2.4). In Africa, uranium reserves prevalent in South Africa, Zimbabwe, and Namibia signify the continent's potential for nuclear energy development. Despite potential benefits, barriers, including high capital costs, regulatory challenges, and workforce limitations, pose significant hurdles to nuclear adoption in many African nations (Sah et al., 2018). Presently, only South Africa operates a nuclear power station with a capacity of 1,800 MW.

While nuclear energy produces minimal greenhouse gas emissions during operation, potential catastrophic failures at plants like Chernobyl (1986) and Fukushima (2011) highlight the significant risks associated with nuclear power. Poor safety protocols and radioactive waste management remain contentious issues in the nuclear energy discourse (Holt et al., 2012). Despite its challenges, nuclear energy provides a continuously stable power source, insulated from environmental disruptions that often affect renewable resources, particularly hydrogen.

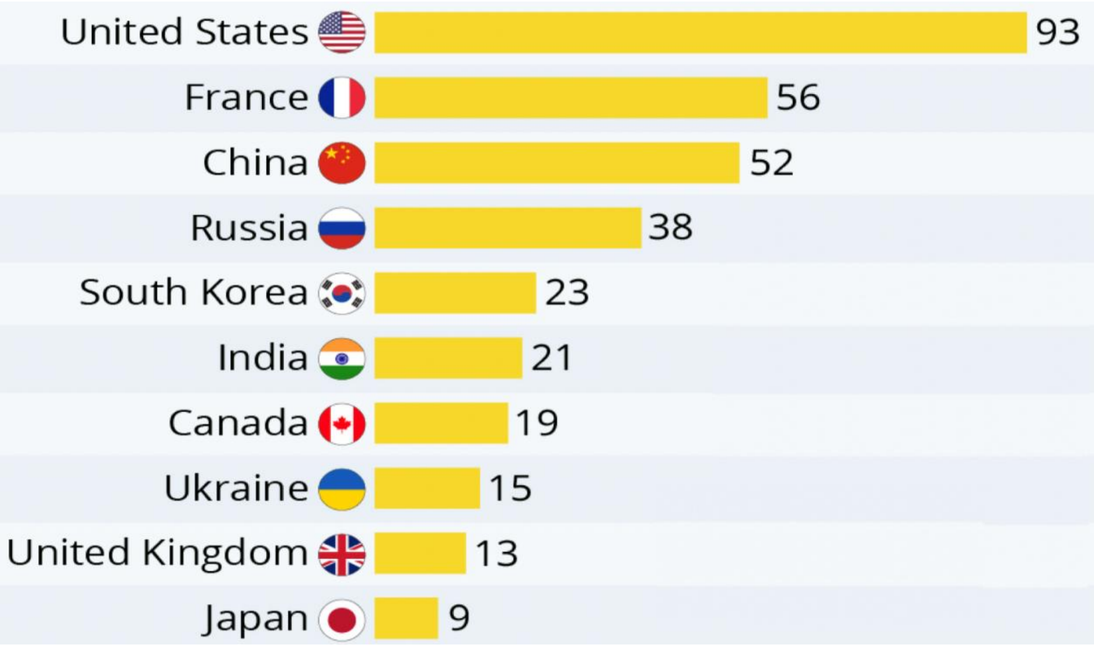


Figure 2.4: Number of Operational Nuclear Reactors by Country in 2021 (Source: BP Statistical Review of World Energy, 2021)

When the hydrocarbon molecules that makeup fossil fuels like methane, petroleum, or coal are burned, the chemical connections between hydrogen and carbon atoms are broken. Fission and fusion reactions are far more energetic than chemical reactions because nuclear forces are significantly stronger than electrical forces. Nuclear reactions produce more than a million times the energy per mass of chemical reactions (pound for pound or kilogram for kilogram). Furthermore, 400 nuclear power plants are now in operation in 26 countries, producing approximately 16% of global electricity demand, with over 4500 reactor years of experience. In several countries, nuclear power has surpassed hydropower as the primary source of electricity. Nuclear power began to enter the electricity market in the 1950s. By 1960, 17 nuclear power reactors with a total electrical capacity of 1,200 megawatts were operational in four countries: France, Russia, the UK, and the USA (Goldemberg, 2009; Sah et al., 2018).

Lower greenhouse gas emissions and lower costs are two advantages of using uranium compared to coal and oil (Holt et al., 2012). A working nuclear power plant can operate continuously for a year, for example, making it more reliable. The plant's operation is also unaffected by weather or foreign suppliers, making it more stable than alternative energy sources. However, the numerous drawbacks of nuclear energy make it unpopular as a source of energy. To begin with, uranium is an unstable material, and special precautions must be taken when shipping, mining, and storing it, as well as when disposing of any of its waste products to avoid the release of harmful amounts of radiation. Nuclear explosions also produce radiation that is harmful to body cells and can cause people to become ill or even die. Years after being exposed to nuclear radiation people can become ill (Goldemberg, 2009; Sah et al., 2018).

A meltdown is a nuclear disaster that can occur when nuclear energy is released into the atmosphere. When an atom's fission reaction becomes uncontrollable, it causes a nuclear explosion that emits a large amount of radiation. Three major nuclear disasters have occurred since the inception of nuclear power, the first of which was the 1979 Three Mile Island accident in the USA, which resulted from a series of apparent errors and equipment problems that resulted in a loss of reactor coolant. In 1986, a significant amount of radiation leaked from the reactor at Russia's Chernobyl nuclear power plant, causing a much larger tragedy. Hundreds of thousands of people were affected by the radiation. Despite natural disasters causing it, the 2011 Fukushima disaster in Japan resulted in the most widespread release of radioactivity when the tsunami knocked out backup power systems needed to cool the plant's reactors, causing fuel melting, hydrogen explosions, and radioactive releases in several of them (Holt, Campbell, and Nikitin, 2012).

2.7.4. Natural Gas

Natural gas has a rich historical background, and it was initially used for religious purposes in ancient Persia. More than 2,000 years ago, the Chinese recognised its energetic potential, employing it to create heat (Mokhatab et al., 2006). In the 1780s, Britain became the first nation to commercialise natural gas, using it to illuminate buildings and street lamps. Today, natural gas is a primary energy source globally, representing a cleaner alternative to coal and oil due to lower carbon emissions. Primary energy is energy embodied in sources that involve human-induced extraction or capture, which may include separation from contiguous material, cleaning, or grading to make the energy available for trade, use, or transformation (Overgaard, (2008). However, its environmental impact must not be overlooked. Natural gas reserves, primarily located in regions such as Russia, Iran, and Qatar, are substantial, with roughly 221.6 trillion cubic feet in sub-Saharan Africa (Smil, 2015). The evolving energy landscape has seen natural gas replace coal and oil in many power plants due to technological advancements in distribution and efficiency (Spa, 2015).

Natural gas serves various applications, including residential heating, industrial manufacturing, and electricity generation. It is a key raw material in countless products, from fertilisers and pharmaceuticals to synthetic materials. However, the combustion of natural gas can release pollutants like nitrogen oxides and sulfur compounds, contributing to environmental issues such as acid rain (Speight, 2018; Kumar, 2017).

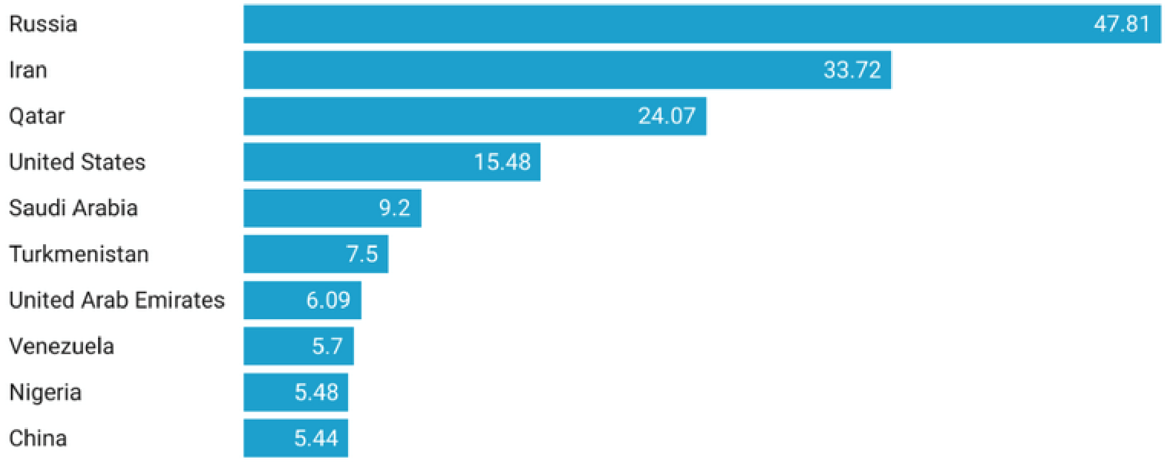


Figure 2.5: Gas Reserves by Country (Billion m³) (BP Statistical Review of World Energy, 2021)

In 1785, a natural gas derived from coal was used to light buildings and lamps, making Britain the first country to commercialise the use of gas. In the late nineteenth and early twentieth centuries, when coal gas was used for street and building illumination, natural gas played a secondary role to coal gas, providing what was referred to as gaslight (Mokhatab et al., 2006). However, as the twenty-first century progresses, natural gas, as one of the three fossil fuels, energises modern economies, owing to the discovery of large natural gas reserves in various countries, as well as improved gas distribution, which allowed for a wide range of applications in homes, businesses, factories, and power plants. Natural gas has largely replaced coal and oil as a fuel in many previously coal- and oil-fired power plants. In natural gas power plants, gas turbines are used to generate electricity, and the hot exhaust gases from the combustion process are used directly (Spa, 2015).

Natural gas has a wide range of uses, including residential, industrial, and transportation. It is also used as a raw material in a variety of goods, including paints, fertilisers, polymers, antifreeze, dyes, photographic film, and pharmaceuticals (Smil, 2015). Natural gas, despite its reputation as a reasonably clean fuel, is capable of emitting pollutants that are harmful to the environment. Natural gas has several advantages over other fossil fuels. The chemical pollutants and carbon dioxide that it contributes to the natural environment are less. If the estimated supplies of unconventional natural gas meet any of the forecasts, supply problems may arise. While methane is the most common component of natural gas, it also contains carbon dioxide (CO_2), hydrogen sulfide (H_2S), mercaptans (thiols; RSH), and trace amounts of other pollutants (Speight, 2018). Acid rain is caused by pollutants emitted into the atmosphere by the combustion of fossil fuels, such as nitrogen and sulfur oxides (Kumar, 2017).

2.8. Renewable Energy Sources

A comprehensive examination of renewable energy sources highlights the critical role of hydrogen in achieving energy diversification, particularly in regions like Africa where renewable resources abound.

The confluence of population growth, rising energy consumption, climate change, and peak oil necessitates a shift toward viable alternatives to fossil fuels. An overreliance on conventional energy sources, particularly oil, coal, and natural gas, has driven economic progress yet poses severe environmental and health hazards. The ongoing climate crisis, along with market fluctuations engendered by oligopolistic production and distribution practices, amplifies calls for alternative energy solutions.

Renewable energy sources are emerging as feasible alternatives, driven by the limited availability of fossil fuels and the urgent environmental imperative to reduce CO_2 emissions. Renewable technologies can harness natural phenomena to provide sustainable energy solutions (Kalogirou, 2013). Currently, these sources meet about 15% to 20% of the global energy demand, with traditional biomass (primarily fuelwood) dominating energy use in many developing countries (Hinrichs and Kleinbach, 2012). Large hydropower plants contribute significantly, accounting for roughly 20% of global electricity output.

Africa stands out with its vast renewable energy resources, including significant hydroelectric capacity, geothermal potential reaching up to 9,000 MW, and extensive biomass, solar, and wind resources (Karekezi and Ranja, 1997). Embracing hydrogen technologies can further empower Africa to develop a sustainable and diversified energy mix, reducing reliance on fossil fuels and transitioning toward a greener economy.

2.8.1. Hydropower

Throughout history, humans have harnessed the power of water for various practical applications. Water wheels, which the Greeks utilised over 2,000 years ago to grind wheat into flour, exemplify the early use of hydropower. Similarly, the Archimedes screw, employed by the Egyptians for irrigation in the third century BC, represents an ancient innovation in water management. The evolution of modern hydropower turbines began in the mid-1700s, culminating in the late 1800s with the introduction of electricity-generating turbines, the first of which was built at Niagara Falls in 1879. Today, hydropower stands as the most common and widely adopted renewable energy source for electricity generation, with over 150 countries actively producing hydroelectric energy.

Approximately 700 gigawatts (GW) of hydroelectric capacity are operational worldwide, contributing about 2,600 terawatt-hours (TWh) per year equating to roughly 19% of global energy production. Brazil holds the most economically exploitable hydropower resources, with an estimated capacity of 800,000 GWh/year (Herzog et al., 2001). Africa also boasts some of the largest dams globally, such as the Grand Renaissance Dam, Aswan High Dam, Cahora Bassa Dam, Gilgel Gibe III Dam, Inga Dam, Kariba Dam, and Merowe Dam, which significantly contribute to the continent's hydropower output.

Dams are often touted for their ability to provide a reliable renewable energy source. Nevertheless, they also face significant drawbacks that warrant critical examination. The construction of dams involves substantial financial investments and long construction timelines, which may require decades of operational use to recoup initial costs (Bagher et al., 2015). Moreover, the environmental impacts of dam projects can be profound. For instance, creating reservoirs frequently leads to the inundation of vast lands, resulting in the loss of flora and fauna and disruption of local ecosystems (Postel & Carpenter, 1997). The Hoover Dam, for example, has been associated with increased seismic activity in its vicinity, illustrating how dam construction can alter geological stability (Fischer et al., 1997). Additionally, dams can obstruct the natural flow of rivers, affecting sediment transport and disrupting fish migration patterns, which can have cascading effects on local biodiversity (Poff et al., 1997). Communities living near such projects may face displacement due to land flooding, with historical examples like the Kariba Dam leading to significant social upheaval and the need for humanitarian initiatives such as Operation Noah to relocate displaced wildlife (Mammides et al., 2019). Given these environmental and social implications, a critical examination of hydropower's sustainability is essential as nations look to harness this energy source responsibly. Figure 2.6 presents the countries with high hydroelectricity generation (billion kWh) capacity globally.

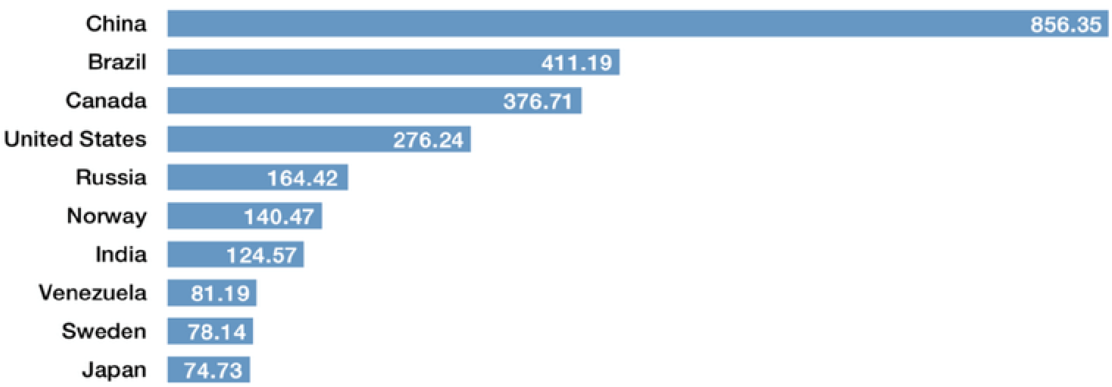


Figure 2.6: Hydroelectricity Generation (Billion kWh) (Source: Statistical Review of World Energy, 2021)

Hydroelectric power generation has numerous advantages, including its transgenerational nature, renewability, flexibility in water flow and output, and the potential for recreational and agricultural use of lake water, which can increase income generation (Bagher et al., 2015). However, hydropower generation is likely negatively impacted because it is sensitive to precipitation amounts, timing, geographical patterns, and temperature. According to Wilbanks et al. (2007), the availability of water has a direct impact on electricity generation. Lower streamflow endangers hydropower generation in some areas, while higher stream flows depending on the timing, may be beneficial (Casola et al., 2005).

Dams, despite being a long-lasting source of energy, are extremely expensive to build and maintain, necessitating decades of operation before they become economically viable (Bagher et al., 2015). Dam construction can harm the geology as evidenced by the Hoover Dam in the USA, which causes numerous earthquakes. These dams influence the natural flow of water downstream and the natural water table levels. Furthermore, flooding large areas of land destroys the natural environment, displaces communities in the flooded valley, and may result in the drowning of humans and animals. Those negative implications were witnessed in the case of Kariba Dam in Zimbabwe, which resulted in Operation Noah.

2.8.2. Wind

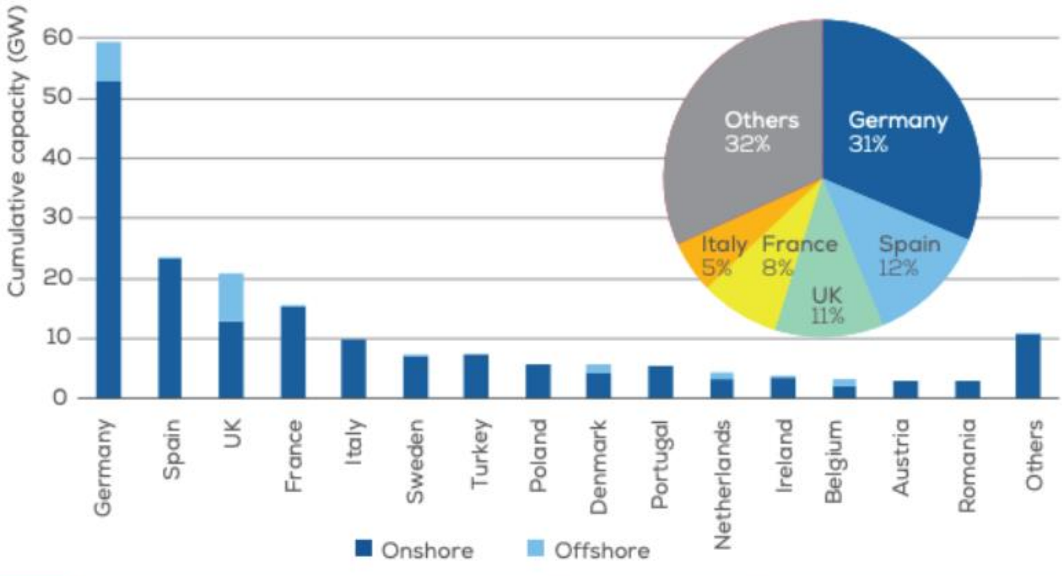
Wind energy possesses significant potential as a clean energy source due to its abundance and its lack of pollution during power generation (Beurskens, 2014). Historically, the utilisation of wind as an energy source spans over 1,500 years, with evidence of vertical-axis windmills used for grain milling documented in Persia in the tenth century, with similar devices emerging in China by the thirteenth century (Sen, 2008). Wind power was once the primary energy source for transportation via sailboats, as well as for grain milling and water pumping. For example, in Zimbabwe, wind energy served crucial functions long before the advent of the steam engine (Nelson, 2009).

Historically, Denmark has been at the forefront of wind energy innovation, with Poul La Cour building an early powered turbine in Askov in 1891 that not only generated electricity but also enabled the production of hydrogen through the electrolysis of water (Herzog et al., 2001). The transformative potential of hydrogen as an energy carrier underscores the importance of advancing wind energy technologies, as excess wind generation could be utilised to produce hydrogen, effectively integrating renewable energy into broader energy systems.

Although Denmark continues to lead in wind turbine manufacturing, the assertion that African countries are larger producers of wind energy requires clarification. Currently, nations such as Egypt, Morocco, and Tunisia are making strides in wind energy development. However, on a global scale, they do not currently rank among the top producers. Instead, historical context reveals that wind energy projects began in North Africa with significant investments made in the last few decades. Notably, African nations, particularly those along coastal areas, harbor substantial untapped wind energy potential, including the Saharan trade winds that stretch from Morocco to Senegal, which offer some of the highest wind energy potentials worldwide.

The environmental implications of wind energy development are multifaceted. On the positive side, wind energy is widely lauded for its eco-friendliness compared to conventional power generation methods, which often emit significant greenhouse gases (Manwell et al., 2010). Wind energy contributes to greenhouse gas mitigation by offering a renewable and readily available power source. Moreover, the increased adoption of wind energy can substantially reduce reliance on fossil fuels. Fossil fuels are expected to be depleted by the end of this century due to their current consumption rates (Tong, 2010). Wind energy also boasts a lower cost per kilowatt-hour (kWh) than solar energy, which positions it as a critical player in future global energy supplies (Tong, 2010).

Nevertheless, wind energy is not without its challenges. Key environmental concerns associated with wind energy development include the interaction of avian and bat species with wind turbines, visual impacts, noise pollution, electromagnetic interference, and land-use changes (Gipe, 1995; Tong, 2010). As the global energy landscape evolves, addressing these concerns will be vital to maximizing the benefits of wind energy while minimizing its ecological footprint.



Offshore	6.4	-	8.2	-	-	0.2	-	-	1.3	-	1.1	-	1.2	-	-	0.1
Onshore	52.9	23.5	12.8	15.3	10.0	7.2	7.4	5.9	4.4	5.4	3.4	3.5	2.2	3.0	3.0	10.8
Total	59.3	23.5	21.0	15.3	10.0	7.4	7.4	5.9	5.7	5.4	4.5	3.5	3.4	3.0	3.0	10.9

Figure 2.7: Onshore and Offshore Wind Turbine Capacity by Country in Europe (GW) (Source: BP Statistical Review of World Energy, 2021).

2.8.3. Geothermal

Geothermal energy harnesses the Earth's internal heat primarily derived from remnants of the planet's formation and the decay of naturally occurring radioactive isotopes (Manzella et al., 2019). This renewable energy source has been utilised for centuries, particularly for heating applications and therapeutic practices, with significant advances in geothermal technologies occurring over the last century. Today, geothermal energy is widely used for various applications, including electricity generation, which remains the most significant use of high-temperature geothermal resources (Manzella et al., 2019).

Historically, geothermal energy has played a pivotal role in heating systems, with the first district heating system installed in Chaudes-Aigues, France, in the 14th century (Herzog et al., 2001). For instance, Reykjavik, Iceland, has been utilising geothermal water for space heating since the 1930s, establishing one of the largest and most recognized district geothermal heating systems. The Larderello region in Italy was the site of the world's first geothermal electricity generation, beginning with an experimental plant in 1904 and leading to commercial generation with a 250-kilowatt plant in 1913. Geothermal energy is broadly categorised into shallow and deep geothermal systems based on the source of heat (Chen, 2011).

Shallow geothermal energy often linked to solar energy stored in the ground, contrasts with deep geothermal energy, which originates from the intense heat found in the Earth's core and mantle. Many geothermal power plants are strategically located near tectonic plate boundaries (such as the Pacific Ring of Fire), in regions with active volcanoes, and in geological hot spots with thin crustal layers, where the feasibility of drilling into hot rocks is promising, as seen in places such as Yellowstone National Park and the Hawaiian Islands (Chen, 2011).

As of 2015, the total global installed capacity for direct geothermal use was approximately 73,290 megawatts (MWt) although previous statements suggesting this figure represents consumption of 163,273 gigatons per year were misleading. Instead, it is more accurate to report that the energy extracted from geothermal sources is equivalent to significant terajoules, facilitating energy needs without depleting resources (Manzella et al., 2019). Pioneering countries in geothermal energy development include China, Turkey, Iceland, Japan, Hungary, and the United States.

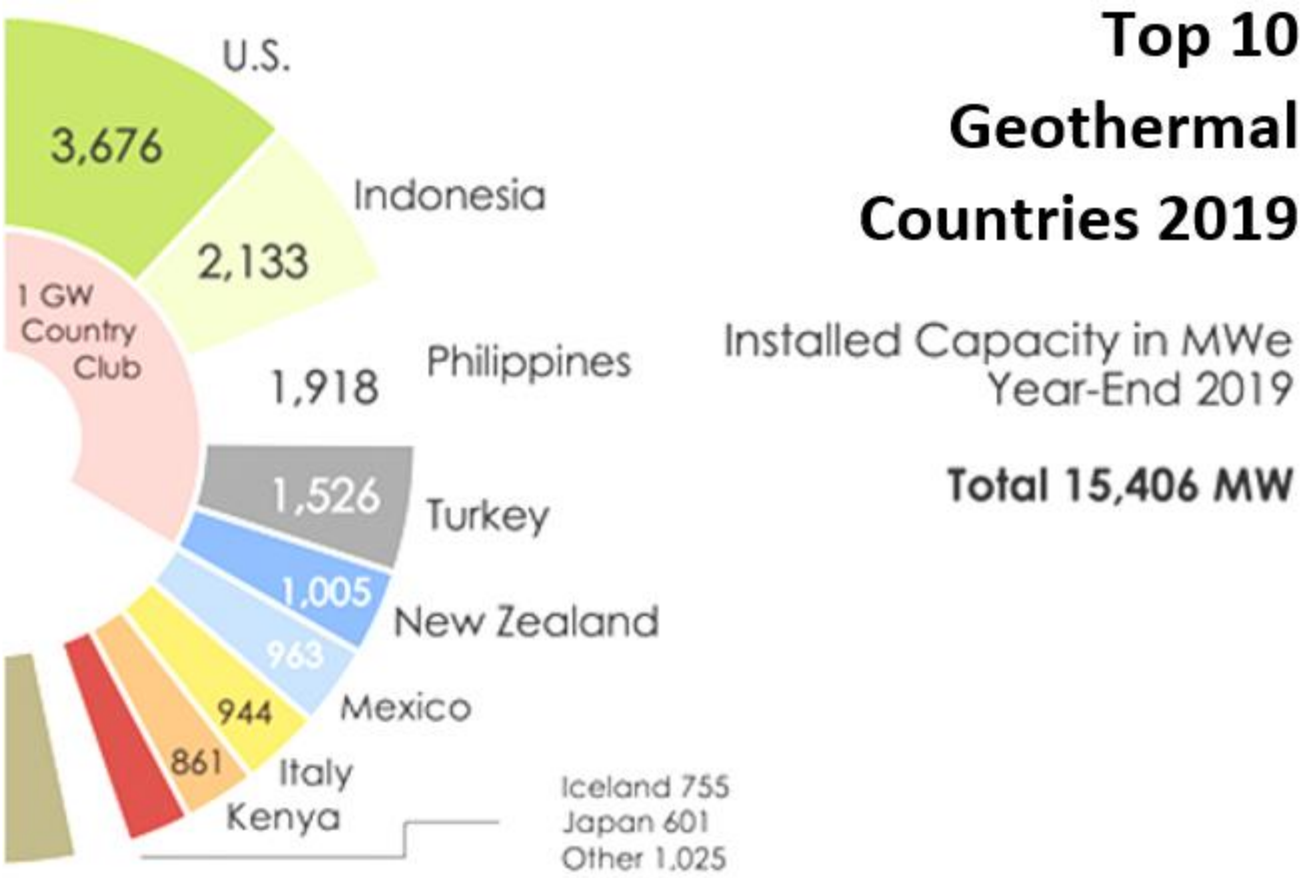


Figure 2.8: Installed Geothermal Capacity in 2019 by Country (Mwe) (Source: ThinkGeoEnergy Research, 2020).

Geothermal energy stands out as a reliable renewable energy source, unaffected by weather fluctuations or water availability unlike hydropower and solar energy. Additionally, geothermal power plants generally require less land for construction, preserving the natural environment. However, the development of geothermal resources is not without its environmental challenges. One concern is thermal pollution resulting from releasing heated water back to the surface, which can disrupt local ecosystems (Manzella et al., 2019).

Furthermore, while the low-to-moderate temperature geothermal fluids employed in many applications may contain trace chemicals, the disposal of these fluids poses limited risks, although wastewater management must be handled carefully to mitigate pollution. A significant issue is the potential for induced seismicity, where geothermal extraction and reinjection processes may trigger seismic events in tectonically active regions near geothermal zones (Manzella et al., 2019). Additionally, while geothermal energy offers substantial benefits, it is important to acknowledge that its development can be capital-intensive, with high initial costs for steam power plants and availability restricted to specific geographic locations.

In the context of hydrogen potential, geothermal energy presents an opportunity for producing hydrogen through electrolysis, utilising excess geothermal energy to power the process. By combining geothermal power with hydrogen generation, a more sustainable and resilient energy system can be established, contributing to the transition toward a hydrogen-based economy.

2.8.4. Solar Energy

The Sun's energy is vast but not limitless. Its availability on Earth can be considered virtually inexhaustible on a relative scale (Tabak, 2009b). Solar energy has historically been the oldest and most fundamental source for nearly all fossil and renewable energy systems (Sen, 2008). Interest in solar energy surged around the 1970s, primarily due to the rising costs of conventional energy sources catalysing the development of innovative solar technologies. The two primary technologies that convert sunlight into useful energy are:

- Solar Photovoltaic (PV);
- Solar Thermal.

Solar photovoltaic (PV) systems directly convert sunlight into electricity (Herzog et al., 2001), while solar thermal power systems use concentrated solar radiation to produce steam, driving turbines to generate electricity (Kalogirou, 2013). The history of photovoltaics dates back over 150 years, with Alexandre Edmund Becquerel first discovering the photovoltaic effect in 1839 (Markvart, 2000). However, significant advancements in solar technology did not take off until the invention of the silicon solar cells in 1954 by Bell. Other notable historical contributions include Augustin Mouchot's solar-powered steam engines and Frank Shuman's solar-powered water pumps, demonstrating the practical applications of solar energy early on (Tabak, 2009b). Solar energy production has seen exponential growth, particularly in China, the USA, India, and Japan among the largest producers globally. As indicated in Figure 2.9, the solar market is also expanding rapidly in Africa, with countries such as South Africa, Morocco, Algeria, Ghana, and Egypt emerging as key players (Tiyou, 2017).

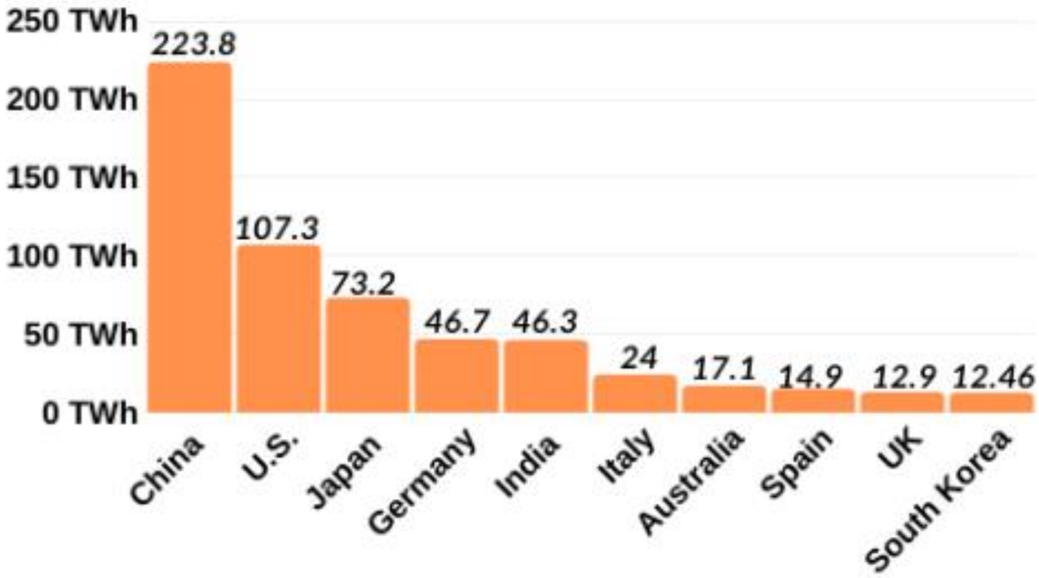


Figure 2.9: The Capacity of Top 10 Countries in Solar Electricity Generation in 2019 (TWh) (**Source:** BP Statistical Review of World Energy, 2021).

Solar energy offers a compelling solution for regions struggling with unreliable power supplies or lacking access to the electric grid such as remote rural areas, developing countries, and even applications in outer space. Furthermore, advancements in solar technologies through which smaller panels have been developed, have enabled widespread access to electricity to charge other personal and household gadgets using solar energy, a trend that is now gaining momentum in rural Zimbabwe (Njeda et al., 2021). Enabled by innovations such as grid-connected PV systems, independent energy production is increasingly feasible, allowing users to sell surplus solar energy back to utility companies. However, the intermittency of solar energy necessitates adequate energy storage solutions to support continuous applications (Foster et al., 2009; Njeda et al., 2021).

Many agricultural processes, such as water pumping and crop production, occur during daylight hours when solar energy is available, which is advantageous in regions with limited access to traditional power sources. PV systems installed in remote areas may be cheaper and require less maintenance than connecting to the grid, which can involve costly infrastructure investments (Foster et al., 2009). Despite the advantages of solar energy, the initial setup costs and the need for effective energy storage systems remain barriers to its widespread adoption without government subsidies (Goffman, 2008). Moreover, while solar energy is less reliant on water than other energy sources, its production can be adversely affected by weather events such as cloudy or dusty days (Aliyu et al., 2018; Baras et al., 2012). As countries like Zimbabwe prioritise food security, the competition for land between agricultural production and solar farms is becoming increasingly pertinent, leading to slower-than-anticipated solar energy adoption (Njeda et al., 2021).

2.8.5. Biomass

Before the rise of fossil fuels during the Industrial Revolution, biomass served as the primary source of energy, predominantly in the form of wood (Chen, 2011). Today, biomass refers to energy derived from organic materials, classified into two categories:

- Woody Biomass (e.g., timber, wood chips)
- Non-Woody Biomass (e.g., agricultural residues, animal waste, and high-energy crops such as corn and sugarcane).

The two types of biomasses are commonly used to generate heat and cook food, with the direct combustion of biomass fuels still prevalent for domestic cooking and heating in many developing countries (Herzog et al., 2001). Biomass also holds exceptional promise as a renewable energy source, offering a means to meet energy demands and enhance fuel security. Biomass ranks as one of the top global energy sources, accounting for approximately 14% of total energy consumption, with the World Bioenergy Association (2019) identifying it as the second or third largest contributor to the global renewable energy mix. Despite a decline in some sectors, this figure has persisted since 2002, challenging assumptions of a significant universal decrease in biofuel utilisation. Ethanol production, for example, has gained traction as a renewable energy source, often blended with petroleum to lower fossil fuel dependence, even in Zimbabwe, where inconsistent production results from various regulatory and infrastructural challenges. In contrast, Brazil has emerged as a leading success story in ethanol production from sugarcane (Chen, 2011).

The benefits of biomass energy include its renewability, lower pollution footprint, and the potential for sustainable energy generation from agricultural and animal waste, which can support local agriculture (Government of Zimbabwe, 2020). Importantly, biogas from biomass is increasingly recognised for its ability to reduce pressure on forest resources for cooking fuel (Balat & Ayar, 2005). However, biomass energy systems also present unique environmental considerations such as potential air pollution, deforestation, and impacts stemming from agricultural practices (World Bioenergy Association, 2019). Additionally, it is essential to factor in the ethical concerns surrounding using agricultural land for biofuel production. This entails discussing the potential consequences, such as food security issues, as prioritising fuel production over food crops may threaten local food supplies and impact farmers' livelihoods. By doing so, we can better understand the complexities involved in the decision-making process of biofuel production in Zimbabwe (Government of Zimbabwe, 2020).

Liquid biomass fuels such as ethanol and methanol produce fewer harmful emissions than conventional gasoline and diesel, benefiting from the inherent neutral carbon cycle of properly managed biomass systems. Nevertheless, the financial barrier to establishing biogas plants can prevent broader adoption, leaving only wealthier populations able to utilise this resource effectively (Balat & Ayar, 2005). Moreover, in a context like Zimbabwe, cultural perceptions about biomass-derived cooking fuels can impede acceptance, particularly when fuels are derived from less appealing sources such as sewage (Winther, 2008). Poorly managed biogas facilities can also pose challenges including space requirements and odor emissions that diminish their viability (Muposhi & Dhurup, 2017). As biomass energy continues to develop, it presents an untapped potential for producing hydrogen through thermochemical processes where high-temperature biomass gases can be utilised in hydrogen production, further enhancing its versatility as an energy source.

2.8.6. Tidal Energy

Tidal energy is a large and consistent source of energy. The commercialisation of tidal energy from tidal rises and falls is currently being pursued using tidal barrage systems (Rourke, Boyle, and Reynolds, 2010). This is a type of hydropower system that uses tidal energy to generate electricity. Tidal power is the only type of energy directly derived from the relative motions of the Earth-Moon system, and to a lesser extent, the Earth-Sun system. According to Tousif and Taslim (2011), the tides are caused by the moon and sun in conjunction with the rotation of the Earth. Since the 11th century, when small dams were built along ocean estuaries and small streams, this type of energy has been harnessed. The relative motion of large bodies of water is used to generate tidal energy. The gravitational attraction of the Sun and Moon causes periodic changes in water levels and associated tidal currents. The magnitude of the tide at a particular location is determined by the changing positions of the Moon and Sun concerning the Earth, the effects of the Earth's rotation, and the local geography of the sea floor and coastlines. Tidal water behind dams is used to power water wheels for milling grains (Katofsky, 2008).

Tidal energy works best in a significant increase of tides of at least 5 meters between low and high tide. The La Rance station in France which has been in operation since 1968 generates 240MW of power from tides, enough to power 240,000 homes. The La Rance power station was built on the Rance River in Brittany between 1961 and 1966 (Kalogirou, 2013; Rourke, Boyle, and Reynolds, 2010). Other tidal energy plants around the world include the Annapolis Royal tidal power generation in the Bay of Fundy in Canada (1982), the Bay of Kislaya in Russia (1968), and another one in the East China Sea (IRENA, 2014).

Many potential locations for tidal barrage construction have been identified worldwide. The difference in water height varies by location and is affected by several factors. Since tidal energy is renewable, no greenhouse gases or other wastes are produced. The tides are completely predictable and there is no requirement for fuel (Yong and Xiaohui, 2010). Although there are no major technical issues to resolve, the current challenges limiting the development of tidal barrage systems include high construction costs and environmental impact (Rourke, Boyle, and Reynolds, 2010).

A tidal barrage requires massive amounts of materials to withstand the loads produced by dammed water. One of the most significant issues in determining whether a site is economically viable for tidal energy extraction is the construction cost. Routine repair is now easier to perform as a result of advancements in turbine designs. Maintenance is no longer considered a developmental issue (Rourke, Boyle, and Reynolds, 2010). Figure 2.10 summarizes the installed tidal energy generation for the top countries.

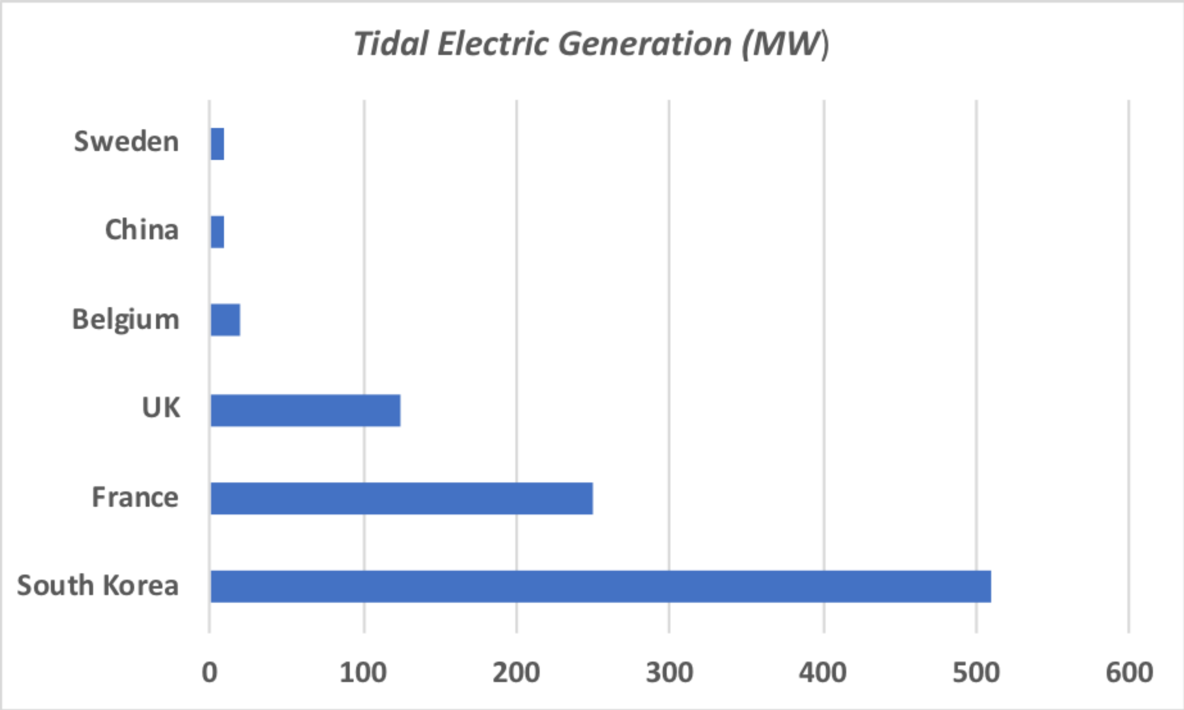


Figure 2.10: Installed Tidal Energy Generation by Country in 2016 (MW).
(Source: BP Statistical Review of World Energy, 2021).

2.9. Hydrogen Energy Vector

This section focuses on hydrogen's potential as a versatile energy carrier. The mechanisms for hydrogen production, including electrolysis and various catalysts, are explored to establish a solid foundation for its practical application.

Hydrogen is emerging as a versatile energy vector that offers significant environmental advantages when utilised as a fuel, primarily due to its capacity to generate electricity with water as the only byproduct. However, this study acknowledges the discoveries of the natural geological occurrence of hydrogen resource in its pure form, despite earlier assertions that hydrogen generally does not exist in its pure form in nature and must be extracted or synthesised from various sources, including water, fossil fuels, and biomass (Kalogirou, 2013; Badea, 2021). Sir William Robert Grove, a Welsh judge, inventor, and physicist, invented the first hydrogen fuel cell in 1839, enabling the combination of hydrogen and oxygen to generate electricity, albeit with modest efficiency compared to modern fuel cells (Wisniak, 2015). Despite the historical context, the role of hydrogen as a critical energy carrier is becoming increasingly recognised in contemporary energy systems.

Table 2.2: Key Milestones in Hydrogen Discoveries and Applications

Year	Discovery/Application	Source
1766	Hydrogen is recognized as an element by Henry Cavendish after evolving hydrogen gas using zinc and hydrochloric acid.	Smith, D. (2006). Hydrogen: A Historical Perspective. ChemTech Publications.
1801	Humphry Davey demonstrates the electrolysis of water, leading to fuel cell principles.	Davey, H. (1806). Researches Chemical and Philosophical.
1806	François Isaac de Rivaz builds the first internal combustion engine powered by a mixture of hydrogen and oxygen.	Hillebrand, J. (1978). Hydrogen and Its Uses in Technology. Hydrogen Energy Publications.
1839	Sir William Grove invents the ‘gas battery,’ known as the first fuel cell, which combines hydrogen and oxygen to produce electricity.	Grove, W.R. (1839). "On the Electro-Chemical Origin of the Electric Current." Philosophical Transactions of the Royal Society.
1842	Gas voltaic batteries demonstrate that hydrogen and oxygen can produce electric current.	Wisniak, J. (2015). Fuel Cells: History and Current Trends. Journal of Chemical Education.
1889	Charles Langer and Ludwig Mond further develop Grove’s invention, formally naming it a fuel cell.	Langer, C. (1889). Review on the Development of Fuel Cells. Journal of Electrochemistry.
1955	The Proton Exchange Membrane (PEM) fuel cell is invented by Willard Thomas	Grubb, W.T. (1959). "A New Type of Fuel Cell." Journal of Electrochemical Society.

Year	Discovery/Application	Source
	Grubb, marking a significant development in hydrogen technology.	
1966	NASA employs fuel cells in space missions for the first time during Gemini missions, showcasing hydrogen's practical applications.	NASA (2016). "The Role of Fuel Cells in Space Missions." NASA Technical Reports.
1970s	The oil crisis prompts the development of alternative energy technologies, including Phosphoric Acid Fuel Cells (PAFC).	International Energy Agency (1981). Energy Technology Perspectives.
1980s	The US Navy incorporates fuel cells into submarine technology for silent operation.	US Navy (1984). "Advances in Fuel Cell Technology for Submarine Applications." U.S. Department of Defense Reports.
2004	Hydrogen fuel cell buses commence operations in London, demonstrating real-world applications of hydrogen technology.	Transport for London (2004). Hydrogen Buses in London - Evaluation Report.
2008	The first hydrogen fuel cell car and airplane successfully operated in the United States, highlighting advancements in hydrogen transport.	Boeing Company (2008). "Hydrogen Fuel Cell Technology". Boeing News Releases.
2015	The UK sees the launch of its first hydrogen refueling station, reflecting the growing infrastructure for hydrogen vehicles.	The United Kingdom Hydrogen and Fuel Cells Association (2015). "UK Hydrogen Refueling Infrastructure Progress Report."

Year	Discovery/Application	Source
2016	The first fuel cell passenger airplane (the HY4) takes flight in Germany, indicating advancements in aviation technology using hydrogen.	DLR (2017). "Hydrogen-Powered Aircraft Take Flight." German Aerospace Center Report.
2017	China's first hydrogen-powered trams are launched, marking a significant milestone in public transport applications.	Zhang, J. (2017). "Innovations in Hydrogen-Powered Public Transport in China." International Journal of Hydrogen Energy.
2018	Germany introduced hydrogen trains, while London's Metropolitan Police added hydrogen fuel cell vehicles to its fleet.	Hydrogen Europe (2018). "Hydrogen Fuel Cell Trains: A European Perspective."
2019	A hydrogen-powered drone successfully operates for over one hour carrying a 5 kg payload in the UK, showcasing the technology's potential.	UK Drone Association (2019). "Hydrogen-Powered Drone Sets Record."

2.10. Hydrogen Production Methods

Outlining hydrogen production methods, including fossil fuel reforming and renewable processes, reveals varied efficiencies and environmental impacts. Assessing these methods enables informed decisions regarding hydrogen integration in energy systems.

Hydrogen found so far in its natural pure gaseous form on Earth is insignificant in quantity, and instead, it must be produced from other compounds. Technically, while reserves of hydrogen have been discovered in various forms, notably as part of certain natural compounds or geological formations, most hydrogen used commercially must be synthesised from sources such as fossil fuels, biomass, and water through processes such as gas reforming and electrolysis (Burton et al., 2021).

Notably, while large-scale hydrogen production has traditionally relied on fossil fuels, recent advancements indicate that more sustainable extraction and production methods are becoming viable. However, the predominant reality remains that hydrogen production will largely continue to involve synthesis through energy-intensive methods (Younous et al., 2018). Hydrogen production methods can be broadly categorised based on the sources utilised: fossil fuels, renewable energy (biomass), and electrolysis. Decisions regarding hydrogen production methods are influenced by various parameters, including cost, efficiency, and environmental impact (Agency of the United States Government, 2009).

As highlighted by Wisniak (2015) and Badea (2021), hydrogen can be derived from a range of sources, each providing unique benefits and challenges. For instance, fossil fuel-based methods offer established and typically cost-effective processes but contribute to greenhouse gas emissions. In contrast, renewable methods, including thermochemical, electrolysis, solar hydrogen, and biological production techniques, promise lower environmental impacts and align with global sustainability goals. Table 2.3 below provides the hydrogen technology development timeline. The timeline chronicles and maintains relevance to hydrogen technology's potential by incorporating the enhancements to and commercialisation of hydrogen in the motor vehicle industry as evinced by the launch of the Toyota Mirai among other earlier vehicles.

Table 2.3: Hydrogen Technology Development Timeline

Year	Technology Development	Source
1625	Johann Baptista van Helmont provided the first description of hydrogen as a distinct substance, laying the groundwork for future studies.	Van Helmont, J.B. (1625). Ortus Medicinae.
1783	Antoine Lavoisier gave hydrogen its name, contributing to its understanding as an element in the modern periodic table.	Lavoisier, A. (1783). "Mémoire sur la composition de l'eau." Mémoires de l'Académie Royale des Sciences.
1783	Jacques Charles successfully flies with his hydrogen balloon “La Charlière,” showcasing the lifting power of hydrogen.	Charles, J. (1783). "Sur le Nouveau Moyens de Mettre en Équilibre les Ballons." Mémoires de l'Académie Royale des Sciences.
1801	Humphry Davey lays out early concepts of the fuel cell, exploring the generation of electric current via chemical reactions.	Davey, H. (1806). Researches Chemical and Philosophical. London: J. Johnson.

Year	Technology Development	Source
1806	François Isaac de Rivaz constructs the de Rivaz engine, marking the first recorded internal combustion engine powered by hydrogen.	de Rivaz, F.I. (1806). "Engine for the Generation of Motion by the Action of Gases." Philosophical Transactions.
1943	Liquid hydrogen is tested as a rocket fuel at Ohio State University, leading to significant advancements in aerospace technology.	Chang, H. (1960). "The Development of Rocket Propellants." Aerospace Engineering Journal.
2015	Toyota launches the Mirai, becoming one of the first commercially available hydrogen fuel cell vehicles to promote broader acceptance of the fuel cell.	Toyota Motor Corporation. (2015). "Toyota Mirai: The Future of Fuel Cells."
2017	The Hydrogen Council is formed to facilitate the global development and commercialisation of hydrogen and fuel cell technologies.	Hydrogen Council. (2017). "Hydrogen: A Renewable Energy Perspective." Hydrogen Council Report.

Source: Author’s Compilation (2024).

Nevertheless, Table 2.4 below clarifies that while the Mirai was launched in 2015, it is part of a broader effort to promote hydrogen fuel cell technology rather than implying it as the first-ever hydrogen fuel cell car.

Table 2.4: Key Hydrogen Fuel Cell Vehicles and Their Significance

Year	Vehicle Model	Significance	Source
1996	Honda FCX	One of the first hydrogen fuel cell vehicles tested for public use.	Honda Motor Co. (1996). "Honda FCX: A Vision of Sustainable Mobility."

Year	Vehicle Model	Significance	Source
2002	DaimlerChrysler NECAR 5	Early production fuel cell vehicle with notable advancements in hydrogen technology.	Daimler AG. (2002). "NECAR 5 – Research on Fuel Cell Technology."
2005	Honda FCX Clarity	Second-generation fuel cell vehicle accessible to customers for lease in select markets.	Honda Motor Co. (2005). "FCX Clarity: The Fuel Cell Vehicle."
2014	Hyundai Tucson Fuel Cell	One of the first hydrogen fuel cell vehicles available for lease in select markets.	Hyundai Motor Company. (2014). "Hyundai Tucson Fuel Cell Launch."
2015	Toyota Mirai	Significant for its role in popularising hydrogen fuel cell technology and infrastructure.	Toyota Motor Corporation. (2015). "Toyota Mirai:

Source: Author Compilation (2024).

Hydrogen is steadily gaining traction as a viable energy source, particularly as countries seek to reduce reliance on fossil fuels and improve energy security. Its potential as an energy carrier for various applications, including transportation and grid energy storage cannot be overstated. Efforts to enhance hydrogen production methods remain crucial for integrating hydrogen into a sustainable energy future.

2.10.1. Hydrogen from Fossil Fuels

This section discusses hydrogen production from fossil fuels, emphasising the main methods, their efficiencies, advantages, and challenges, particularly in the context of hydrogen's potential.

2.10.2. Steam Reforming (SR)

Steam reforming is the most widely used method of hydrogen production, accounting for approximately 90% of global hydrogen output in 2018 (Younous et al., 2018). It utilises natural gas or lighter hydrocarbons due to their favorable hydrogen-to-carbon ratios. The process operates efficiently at temperatures between 180 °C and 500 °C, where methane is reacted with high-temperature steam (often around 250 °C) in the presence of nickel catalysts to form syngas which is a mixture of hydrogen (H_2) and carbon monoxide (CO) (Bakey, 2015).

While steam reforming is cost-effective with reported thermal efficiencies of 70-85%, it has significant environmental drawbacks, such as high CO_2 emissions (~7.05 kg CO_2 per kg H_2 produced) (Turner, 2004). The process's reliance on fossil fuels raises sustainability concerns, especially as the global energy landscape shifts towards renewable sources.

In the practical context of this study, while steam reforming remains economically advantageous, its negative environmental impact and dependency on fossil fuels necessitate exploring alternative hydrogen production methods. In this case, hydrogen is produced via a steam-carbon reaction (Lwin et al., 2000). A light hydrocarbon feedstock, such as methane, is reacted with steam at around 1500 °F and 250 °C, in the presence of a catalyst. This results in the synthesis of a gas, which is a mixture of carbon monoxide and hydrogen. The reaction can be represented chemically. Its competitive advantage stems from its high operational efficiency and low operational and production costs (Turner, 2004). The following diagram is a network of reforming reactions for hydrocarbons and methanol used as feedstocks.

$$C_mH_n + mH_2O = mCO + (m + 0.5n)H_2 \qquad (1)$$

$$C_mH_n + 2mH_2O = mCO_2 + (2m + 0.5n)H_2 \qquad (2)$$

$$CO + H_2O = CO_2 + H_2 \qquad (3)$$

$$CH_3OH + H_2O = CO_2 + 3H_2 \qquad (4)$$

The whole process comprises two stages:

I. A tubular catalytic reactor is fed with raw hydrocarbon material and steam. In this process, syngas (H_2/CO gas mixture) with a lower CO_2 content is produced by combusting a portion of the raw materials (heating gas) inside the reactor with oxygen or air.
II. The cooled product gas is fed into the CO catalytic converter, which uses steam to partially convert carbon monoxide into carbon dioxide and hydrogen.

Any light hydrocarbon feedstock can be vapourised and used to produce hydrogen, but methane is preferred because it offers the highest hydrogen-to-carbon ratio of any hydrocarbon (Younous, 2018). The steam reforming catalytic process requires a raw material free of sulfur-containing compounds to avoid catalyst deactivation. The SR process requires relatively low temperatures, such as 180 °C for methanol and oxygenated hydrocarbons, and more than 500 °C for most conventional hydrocarbons. Non-precious metals (typically nickel) and precious metals from Group VIII elements (typically platinum or rhodium) are the two types of catalysts. On a commercial scale, the heat efficiency of hydrogen production by the SR of the methane process is approximately 70–85% (Bakey, 2015).

The disadvantage of hydrogen production through the steam reforming of methane process is the high CO_2(g) production (approximately 7.05 kg CO_2(g)/kg H_2). The feedstock material's H:C atom ratio is a critical factor in characterising the steam reforming process. The lower the carbon dioxide emissions, the higher this ratio. A membrane reactor can replace both reactors in a conventional SR process to achieve the overall reaction. Methane steam reforming produces a mixture of CO_2(g), CO, and H_2. At 200-300 °C, syngas (synthesis gas) is converted to methanol via Cu/ZnO catalysts (Silveira, 2016).

Catalysts can be added to the partial oxidation system to lower the operating temperature, i.e., 700-1000 °C. The crude hydrogen produced by steam reforming may contain impurities such as carbon dioxide, carbon monoxide, methane, and water vapor. As a result, hydrogen must be purified further via absorption and adsorption processes. While steam reforming has little environmental impact as long as natural gas or other light hydrocarbon feedstocks are available, it remains the most cost-effective method of producing hydrogen at present (Rauch, Hrbek and Hofbauer, 2014; Bakey, 2015).

The advantages of SR over other methanol conversion methods in terms of low CO production do not apply to other hydrocarbon fuels. This is because heavier fuels (those with C-C bonds) necessitate a different conversion mechanism; thus, SR does not provide the same benefits as Partial Oxidation or Autothermal Reforming (ATR) for these fuels. Figure 2.11 summarizes the steam reforming process according to Bakey (2015). The Steam Methane Reforming procedure is divided into five distinct steps as represented in the following flow diagram.

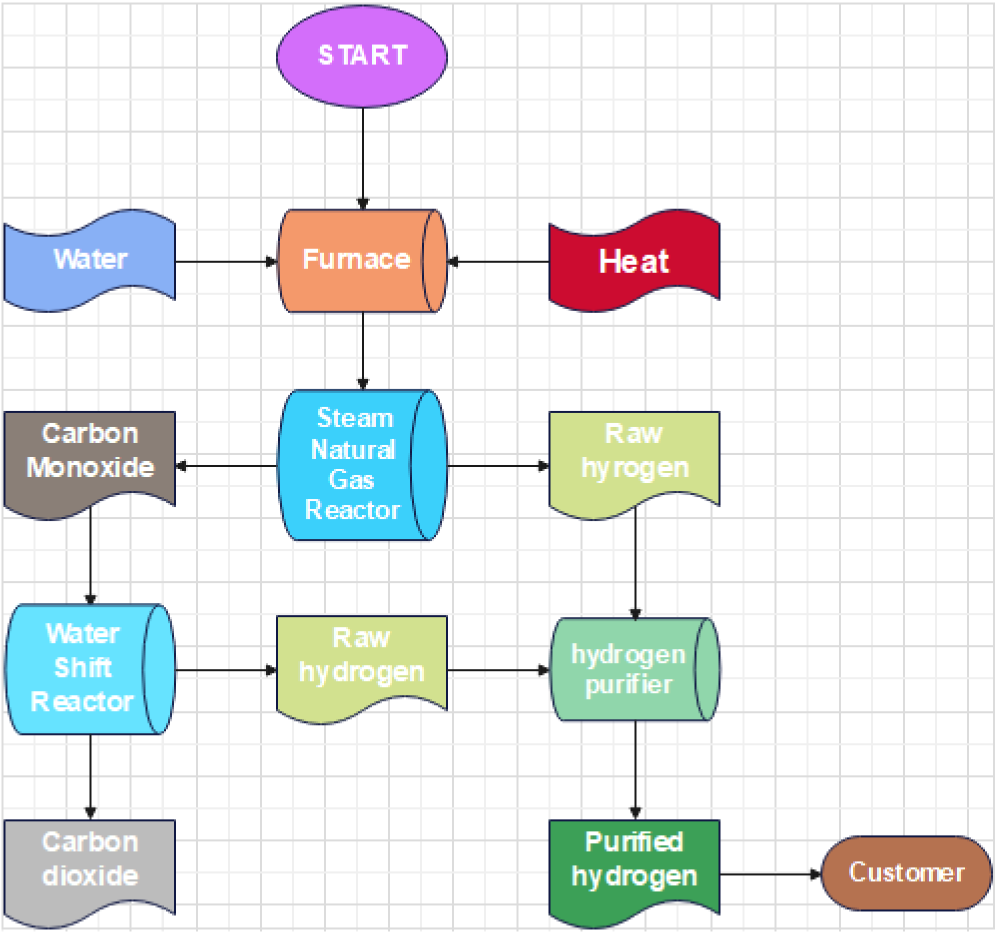


Figure 2.11: Summary of the Steam reforming process (*Adapted from Bakey, 2015).*

2.10.3. Partial Oxidation

Partial oxidation (POx) is used in large-scale hydrogen production, particularly in fuel cell applications (Silveira, 2016). This exothermic reaction involves limited oxygen to convert hydrocarbons (such as methane) into H_2 and CO. Operating at flame temperatures of 1300-1500 °C, POx can produce hydrogen faster than steam reforming with a smaller reactor footprint.

Despite its advantages in reaction speed and reactor size, POx poses challenges related to temperature control and coking, which can lead to operational inefficiencies. Furthermore, it generates a gas mixture that includes unwanted by-products, necessitating further purification. From a flow and cost perspective, POx's cheaper reactor setup can be offset by higher downstream processing costs, making it essential to evaluate its integration into hydrogen production schemes (Silveira, 2016).

This process initially produces less hydrogen per unit of input fuel than steam reforming of the same fuel, as seen in partial oxidation chemical reactions (ibid). CO_2(g), H_2(g), CO(g), H_2O(s), CH_4, hydrogen sulfide (H_2S), and carbon oxysulfide (COS) are present in the partial oxidation gas mixture. While the reactor is less expensive than steam reforming, the subsequent conversion raises the overall cost of this technology. Because the process does not require the use of a catalyst, sulfurous elements in natural gas are not removed, which reduces the catalyst's efficiency in the long term. Temperature control is difficult, however, due to coke and hot spot formation caused by the exothermic nature of the reactions. Natural gas conversion catalysts are typically made of Ni or Rh. Due to the high operating temperatures (> 800 °C) and safety concerns associated with thermal management, they may be problematic for practical and compact portable devices (Silveira, 2016).

This reaction contributes to the maintenance of equilibrium between the individual reaction products:

$$CH_4 + {}^1/_2\, O_2 = CO + 2H_2$$

$$CH_4 + O_2 = CO_2 + 2H_2$$

$$CH_4 + H_2O = CO + 3H_2$$

2.10.4. Autothermal Reforming

Autothermal reforming (ATR) combines steam reforming with partial oxidation, taking advantage of the heat generated by the combustion of fuel and steam. This process occurs under controlled thermal conditions, allowing for a balanced reaction that mitigates the endothermic nature of steam reforming (Silveira, 2016). ATR has gained attention for its ability to maintain operational stability with low energy inputs and operational costs.

In terms of practicality, ATR facilitates rapid start-and-stop cycles, which can be advantageous in fluctuating energy scenarios. The ability to manage the H_2 to CO ratio effectively via adjustments in reactant ratios highlights ATR’s versatility in differing feedstock contexts (Silveira, 2016).

It has sparked interest by eliminating disadvantages of other reactions, such as the low energy requirement to compensate for the effects of endothermic (such as steam reforming) and exothermic (such as pyrolysis) processes. This is accomplished by placing the two reforming reactions in close thermal contact or by combining them in a single catalytic reactor. Once the reactor has reached operating temperature, the fuel, steam, and air are all fed into it at the same time. When the reactants are ignited, the ideal products of hydrogen and carbon dioxide are formed.

According to Silveira (2016), it has been discovered that on noble metal-based catalysts, ATR generally follows equilibrium concentrations in the output gas based on the reaction temperature. It also has low specific consumption and can control the H_2/CO ratio effectively by adjusting the oxygen and steam feed rates. ATR has the advantage of not requiring external heat, making it easier and less expensive to implement compared to methane SR. Another significant advantage of the ATR process over the SR process is that it can be stopped and restarted quickly while producing more hydrogen than POx alone.

ATR operates similarly to SR with an additional Catalyzed POx (CPOx) step. This is because these exothermic steps (in CPOx) are fast, and the resulting heat can be used to sustain the SR steps. Thus, ATR is often referred to as autothermal or thermally neutral. The typical ATR equation of a hydrocarbon is shown in the following equation:

$$C_mH_n + 0.5mO_2 + 0.5mH_2O = mCO + (0.5m + 0.5n)H_2$$

Auto-thermal reforming has advantages. It does not require external heat, it is simple and less expensive, and it can be shut down. After that, it still starts very rapidly. One of its main disadvantages is that damage to the catalyst may take place due to heat and mass transfer limitations. These attributes warrant consideration to guide hydrogen potential innovation research.

2.10.5. Water-Gas Shift, Preferential Oxidation, and Methanation

The water-gas shift (WGS) reaction improves hydrogen yield post-reforming by converting CO and steam into CO_2 and H_2. This usually involves a two-step process that operates efficiently at varying temperatures (Silveira, 2016). The integration of WGS into hydrogen production systems enhances overall H_2 output while maintaining lower CO levels in final products, which is vital for applications in fuel cells.

In light of the study's focus, while detailing the WGS process, it is critical to recognize its significance in refining hydrogen purity levels essential for fuel cell operation, where even trace contaminants can impede performance.

To promote fast kinetics, a high temperature is usually preferred. However, this results in high equilibrium carbon monoxide selectivity and a lower hydrogen product yield. Consequently, the CO content of syngas is reduced in a two-step process involving a high-temperature water-gas shift reaction, known as the "HTS" and "LTS" processes. In the first step, the CO concentration is reduced from 10% to 3% using a Fe_3O_4/Cr_2O_3 catalyst at temperatures ranging from 310–450 °C. In the second step, the CO content is reduced to 500 ppm using $Cu/ZnO/Al_2O_3$ catalysts at temperatures ranging from 180–250 °C. A preferential oxidation (PrOx) reactor or a carbon monoxide selective methanation reactor is used to further reduce the carbon monoxide content in the product gas.

The term "selective oxidation" is sometimes used instead of "preferential oxidation." The reduction of carbon monoxide within a fuel cell, most commonly a proton-exchange membrane (PEM) fuel cell, is known as selective oxidation, whereas preferential oxidation occurs outside of the fuel cell in a reactor (Silveira, 2016). The primary advantage of this reaction over steam reforming is that it does not require external heat and thus does not necessitate heat exchangers, resulting in a simpler and more compact design with a lower capital cost. Most often, the WGS has been carried out in two reactors, one of which is a high-temperature reactor at 350–500 °C and the other is a low-temperature reactor at around 200 °C.

Fe-Cr-based catalysts are predominantly used in high-temperature reactors, while Cu-based catalysts are utilised in low-temperature reactors.

After the biomass gasifier, a water-gas shift reactor is installed to produce hydrogen from biomass gasification, and the final gas consists primarily of hydrogen and CO_2(g). A membrane can then be used to easily separate hydrogen. Ultrapure hydrogen can be produced due to this process. Carbon monoxide from the reforming reaction is consumed while hydrogen is produced in the water-gas shift reactor. This reactor contains both water and an iron-chrome-based catalyst that converts steam (H_2O) into oxygen (O_2) and hydrogen (H_2). The carbon monoxide (CO) produced by the reforming reaction is combined with oxygen to produce carbon dioxide while hydrogen is being collected.

2.10.6. Hydrogen Production via Coal Gasification

Coal gasification presents a viable alternative for hydrogen production while leveraging abundant coal resources (Turner, 2004). The process typically entails partial oxidation followed by water-gas shift reactions. While this method benefits from current coal availability and technology, it also encounters significant environmental concerns due to the high CO_2 emissions associated with coal combustion.

Given the project's aims, assessing coal gasification's compatibility with broader hydrogen strategies is relevant, particularly regarding its Technology Readiness Level (TRL), cost implications, and potential integration with carbon capture initiatives. At high temperatures, finely ground coal reacts with steam and oxygen (Turner, 2004):

$$3C + O_2 + H_2O = 3CO + H_2$$

Hydrogen is produced during the steam gasification reaction with coal. The oxygen gasification reaction, which burns a portion of the coal with oxygen, provides the heat required for the steam gasification reaction. The water-gas shift reaction, which converts carbon monoxide from the steam gasification reaction into hydrogen, increases the hydrogen yield:

$$CO + H_2O = CO_2 + H_2$$

The hydrogen-producing process from coal is similar to that of steam reforming but it is significantly more challenging to carry out because coal is difficult to handle as a solid. It is relatively unreactive and necessitates the periodic removal of ash present in coal as slag from the gasification reactor. One disadvantage of this method is that coal may contain a high amount of sulfur that must be removed. Another disadvantage of coal feed is that it has a lower hydrogen/carbon ratio (around 0.8) than methane (Turner, 2004; US Government, 2009).

2.10.7. Hydrogen from Renewable Sources

Beyond hydrocarbon reforming, hydrogen production through renewable processes is essential for sustainable energy strategies. Key methods include biomass conversion, electrolysis, and thermochemical water splitting, which collectively represent non-fossil fuel-based routes to hydrogen (Kalamaras & Efstathiou, 2013). Turner (2004) and the Agency of the United States Government (2009), among many others, affirm that these processes include biomass-based methods (e.g., gasification, pyrolysis, advanced gasification, fermentation, biophotolysis, and aqueous phase reforming), and hydrogen production from water (e.g., electrolysis, photoelectrolysis, and thermochemical water splitting).

2.10.8. Biomass Hydrogen Production

Biomass conversion, including gasification (pyrolysis, advanced gasification) and biological methods (fermentation, biophotolysis), harnesses organic materials for hydrogen production, positioning it as a promising renewable source (Kalamaras & Efstathiou, 2013). Biomass's accessibility and diversity make it a key player in diversifying hydrogen stocks. However, logistical challenges, including transport and storage issues regarding biomass materials, can heighten production costs and complexities, necessitating local supply chain assessments in project considerations (Ahlstrom, 2020). Biomass comes from various sources, including animal waste, municipal solid waste, crop residues, short-rotation woody crops, agricultural wastes, sawdust, aquatic plants, and short-rotation herbaceous species (e.g., switchgrass) among others. Biomass tends to be bulky, deteriorates over time, and is difficult to store and handle. One disadvantage of this technology is the vast number of resources required to transport large amounts of biomass to the central processing plant. High logistics costs associated with the gasification plants, and the removal of "tars" to acceptable levels for pure hydrogen production, currently limit the commercialisation of biomass-based hydrogen production.

There are three steps to producing hydrogen from biomass:

1. Woody biomass is thermally gasified in the first step, producing a synthesis gas primarily composed of combustible gases like H_2 and CO.
2. This step involves treating the synthesis gas, fine particle filtering, desulfurization, and tar wash-cracking. Reforming and water-gas shift reactors can increase the hydrogen content of syngas even more.
3. Treated gas is processed (via membranes, for example) to produce pure hydrogen.

Gasification is the thermochemical conversion of solid biomass, occurring after the drying and pyrolysis steps. Biomass is gasified in this process, producing a combustible gas that can be used in a combined heat and power apparatus (e.g., microturbines, fuel cells, internal combustion engines). Thermal gasification of biomass is a well-recognised process with a wide range of applications in the field of energy production.

2.11. Emerging Methods

Emerging hydrogen production technologies such as plasma reforming and ammonia cracking, introduce innovative avenues for hydrogen generation. Plasma reforming exploits high-energy input to drive reactions at lower costs and with fewer operational complexities (El-Shafie, Kambara, and Hayakawa, 2019). Similarly, ammonia cracking demonstrates potential through its endothermic reactions that yield hydrogen without the high-pressure requirements of other methods (Itoh et al., 2002).

While traditional hydrogen production methods like steam reforming dominate current technologies, the evolution toward sustainable and renewable production routes provides the foundation for a low-carbon hydrogen economy. Each method carries its unique advantages and challenges, which must be weighed carefully in the context of scalability, environmental impact, and practical application to maximise hydrogen's potential as a clean energy source.

2.11.1. Electrolysis and Thermochemical Water Splitting

Electrolysis is a method that facilitates the direct production of hydrogen from water using renewable electricity, making it an essential process for hydrogen generation (Burton et al., 2021). This method supports the integration of energy sources such as solar and wind power, fostering a transition away from fossil fuels. Thermochemical water splitting employs high temperatures from sources like nuclear reactors or concentrated solar power, offering another efficient pathway for hydrogen production (Han et al., 2007). This dual approach underscores the adaptability and scalability of hydrogen production technologies necessary for a sustainable energy future.

2.11.2. Superheated Steam

Many obstacles must still be overcome for biomass gasification technology to become more competitive in the energy industry. Among these are the variability of fuel supply and the relatively low net calorific value of the gas produced, particularly in advanced technologies such as autothermal gasification. These constraints include a lack of consistent fuel supply, a low net calorific value of the produced gas (particularly in cutting-edge autothermal gasification technology), and numerous transportation and storage issues that make biomass more challenging to handle than fossil fuels. Addressing these issues will be crucial in optimizing biomass gasification for hydrogen production and integrating it into broader energy solutions.

2.11.3. Pyrolysis and Co-pyrolysis

Hydrogen can be efficiently produced through pyrolysis, a process that converts biomass into liquid bio-oil by thermally degrading organic materials in the absence of water and air. Pyrolysis is categorised based on operating temperatures into low (up to 500 °C), medium (500–800 °C), and high (over 800 °C). During this endothermic process, biomass undergoes a complex series of reactions; ultimately yielding bio-oil characterized by 85% oxygenated organics and 15% water when produced at temperatures between 450 and 550 °C.

The bio-oil can then undergo steam reforming in the presence of nickel-based catalysts at temperatures ranging from 750 to 850 °C, followed by water-gas shift (WGS) reactions to enhance hydrogen yield. The product fractions be they solids, liquids, and gases, are influenced by critical parameters such as temperature, heating rate, and vapor residence time. Notably, when conducted without the presence of water or air, the process minimises CO_2 emissions. However, varying operational conditions can lead to effluents, underscoring the importance of optimising these parameters for cleaner production.

One of the key impacts of pyrolysis is its potential to significantly alleviate CO_2 emissions, particularly when configurations allow for maximum carbon recovery as solid by-products, thus reducing environmental impacts. This method promises not just fuel flexibility. It also contributes to lower overall COx emissions, making it a crucial technology in the shift towards renewable hydrogen production. However, care must be taken to manage carbon fouling, which can inhibit system performance.

The possibility of fouling caused by the resulting carbon is one disadvantage of this approach. The reactions can be presented as:

- **Pyrolysis:**

$$Biomass = bio{\sim}oil + char + gas$$

- **Reforming:**

$$Bio{\sim}oil + H_2O = CO + H_2$$

- **Shift:**

$$CO + H_2O = CO_2(g) + H_2$$

2.11.4. Advanced gasification

Supercritical Water Gasification (SCWG) represents a significant advancement in gasification technologies. SCWG uses water as a reaction medium to convert biomass into hydrogen-rich syngas at supercritical temperatures (374 °C) and pressures (22.1 MPa). This method boasts the advantage of high-pressure hydrogen production, reducing the need for post-process compression and optimising overall efficiency.

In the SCWG process, biomass components such as cellulose, hemicellulose, and lignin undergo hydrolysis and degradation, yielding simpler compounds like sugars and phenolics (Kıpçak & Akgün, 2015). The integration of heterogeneous catalysts enhances the conversion efficiency of the process, yielding not only hydrogen but also CO_2, CO, and CH_4 depending on reaction conditions.

Despite its advantages, SCWG presents challenges, including concern about reactor material durability due to corrosion and plugging. Moreover, preheating requirements increase operational costs. However, the ability to utilise wet biomass without energy-intensive drying processes signifies a decisive benefit for commercial viability. Under advanced gasification, there are two types presented below:

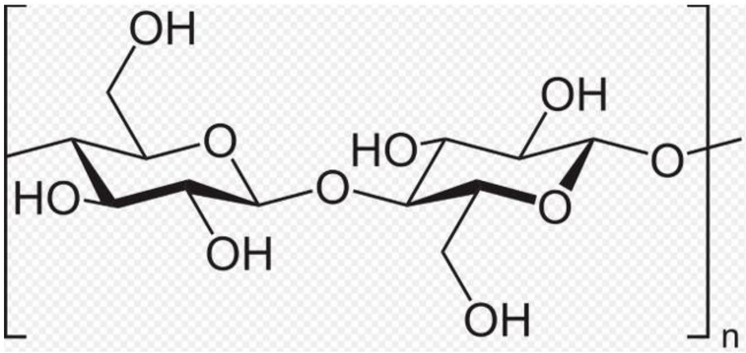
2.11.5. Supercritical Water Gasification (SCWG)

Supercritical water gasification is a variation of conventional gasification. It employs water as the reaction medium to convert biomass into hydrogen-rich syngas. Supercritical water works as both a reagent and medium at 374 °C and 22.1 MPa. An added advantage is its high-pressure H_2 production, which cuts down the compression energy costs during its storage. At the supercritical point, water can form ions that facilitate the degradation of biomass components:

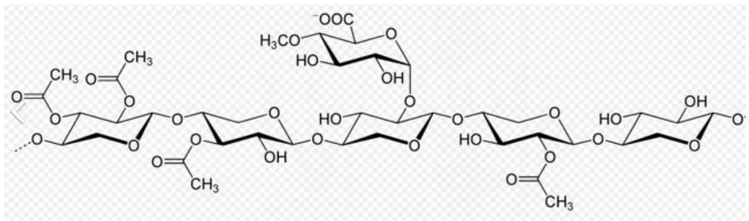
- Cellulose and hemicellulose (Figure 2.12)
- Lignin (Figure 2.13)

Under hydrolysis, cellulose, and hemicellulose hydrolyze to yield C5 and C6 sugars while lignin degrades into phenolic components as well as guaiacols and syringols (Kıpçak & Akgün, 2015). In the SCWG regime, these degradation products are further converted into simpler compounds like acids, alcohols, phenols, aromatics, and aldehydes. With the assistance of different heterogeneous catalysts, gases such as H_2, CO_2(g), CO, and CH_4 are produced based on WGS, methanation, hydrogenation, and other reactions.

Supercritical water gasification (SWG) can gasify biomass at a high conversion rate, producing H_2 and CO_2(g) as product gases. One advantage of the SWG gasification method over conventional techniques is that only one reactor is required. Furthermore, at low temperatures (below 700 °C), this method is highly efficient and does not require lowering the moisture content of the fuel, allowing for the use of wet biomass. As a result, solid fuels can avoid the energy-intensive drying processes that are usually needed. Moreover, supercritical water can dissolve most organic compounds and has excellent mass transfer properties. However, challenges remain concerning corrosion and plugging, as well as economic issues, because this approach necessitates the use of external energy to preheat both the biomass and the reactor, which raises overall costs.



(a)



(b)

Figure 2.12: Chemical structure of (a) cellulose and (b) a common motif of hemi-cellulose (Wang *et al.*, 2016)

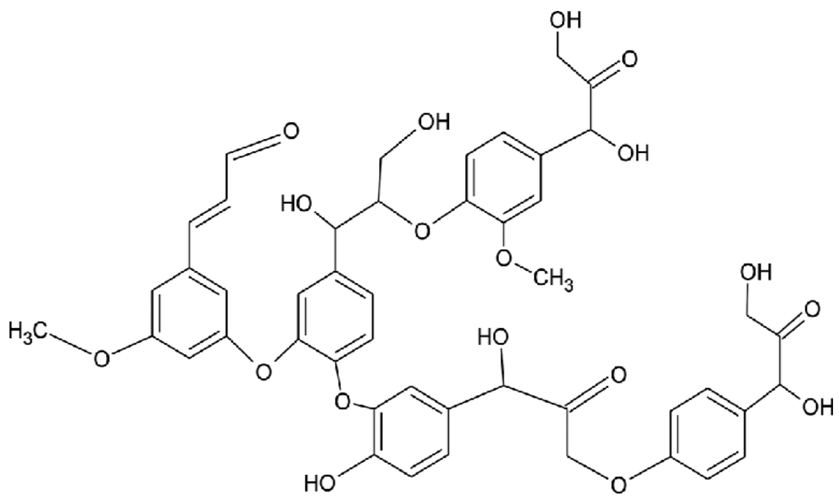


Figure 2.13: Representative chemical structure of lignin (Setua *et al.*, 2000)

2.11.6. Sorbent Enhanced Gasification (SEG)

Sorbent Enhanced Gasification (SEG) incorporates two reactors: one for gasification and another for absorption, where carbonaceous fuels are fed alongside steam to initiate gasification, producing a mixture of H_2, CO, and CO_2 (Florin & Harris, 2007). The calcium oxide sorbent effectively absorbs the produced CO_2, converting it into calcium carbonate, which aids in maintaining a favorable reaction environment.

The heat released during this CO_2 absorption process is repurposed to drive the endothermic gasification of biomass, enhancing the system's energy efficiency. Notably, the regeneration of CaO involves heating the calcium carbonate, which poses additional energy considerations.

The selection of catalysts is crucial for optimising hydrogen production through SEG. Focus on materials with high-temperature stability and non-corrosive properties, including carbon nanotubes and nickel-based catalysts. SEG's advantages include opportunities for substituting conventional fossil fuels with low-cost producer gas, leading to reduced emissions (NOx and particulate matter). However, it's essential to address potential operational complexities and environmental impacts, particularly in sourcing biomass sustainably.

The criteria for selecting catalytic materials in hydrogen production from biomass involve the following:

- High-temperature stability
- Reactivity to other materials in the process (must be non-reactive)
- Corrosivity (non-corrosive material applicable, e.g., carbon nanotubes, nickel, platinum, ruthenium, activated carbon, palladium, alumina)

Advantages:

- Opportunity to substitute natural gas with low-cost producer gas.
- Lower NOx, CO, and particulate emissions.
- Biomass is abundantly available as a renewable energy source.
- It is generally less expensive than fossil fuels.

Disadvantages:

- Excessive utilisation of wood leads to deforestation.
- Biomass energy is not as efficient as fossil fuels.
- Complex operations due to the need to control air and solid fuels.
- High amounts of ash and dust particles remain in the gas.

2.11.7. Biological Hydrogen Production (BHP) Process

The Biological Hydrogen Production (BHP) process has emerged as a promising alternative to traditional hydrogen generation methods. This process harnesses renewable sources like biomass, water, and organic wastes to produce hydrogen through biological or photo-biological mechanisms. The biological conversion of biomass relies heavily on the preparation of raw materials suitable for fermentation by microorganisms. The various biological methods for hydrogen production can be classified into:

- Biophotolysis (direct and indirect)
- Fermentation (photofermentation and dark fermentation)
- Biological gas shift reactions
- Microbial electrolysis cells (MEC)
- Major enzymes
- Aqueous phase reforming

This diversity underscores the versatility of biological processes in hydrogen extraction.

2.11.8. Bio photolysis

Bio photolysis is a biological method for hydrogen production that exploits the photosynthetic capabilities of microorganisms such as cyanobacteria and eukaryotic microalgae. Direct bio photolysis uses these organisms to split water directly into hydrogen and oxygen (Show & Lee, 2013). In contrast, indirect biophotolysis entails fixing carbon dioxide into stored substances (e.g., glycogen) and subsequently converting these into hydrogen. To determine commercial viability, bio photolysis must achieve a solar conversion efficiency of close to 10% (Bolton, 1996). This benchmark underscores the ongoing technological challenges that need to be overcome for practical application.

Benemann (1998) defines biophotolysis as the use of microalgae cyanobacteria and eukaryotic microalgae to generate hydrogen from sunlight and water. Algae can be referred to as pilot-like organisms that are usually photosynthetic and aquatic but do not have true roots, stems, leaves, vascular tissue, or simple reproductive structures (Randrianarison & Ashrat, 2017). Biophotolysis can be divided into two categories: direct and indirect biophotolysis.

Direct biophotolysis capitalises on the photosynthetic capability of algae and cyanobacteria to split water directly into oxygen and hydrogen (Show & Lee, 2013). Indirect bio photolysis involves microalgae cultures that first fix carbon dioxide (CO_2) into stored substances (e.g., glycogen, starch, etc.), which are then converted in the second process to hydrogen.

2.11.9. Microbial Electrolysis Cells (MEC)

Microbial electrolysis cells (MECs) represent a novel approach to hydrogen production through electrohydrogenesis. Exoelectrogenic bacteria consume organic substrates, such as acetate and glycerol, converting them into by-products, including hydrogen, methane, and other metabolites (Badwal, 2014).

By transferring electrons to an anode, these microorganisms facilitate the generation of hydrogen gas in conjunction with an external voltage.

MEC designs can vary from single-chambered to double-chambered systems, with efficiency influenced by the following factors: pH, electrode materials, and temperature (Waqas et al., 2018). Challenges associated with MEC commercialisation include energy losses from overpotential resistances and the prevalence of methanogenesis, which can undermine hydrogen yields by converting H_2 into methane (CH_4) (Cheng & Logan, 2007).

The different designs of MEC systems include single-chambered and double-chambered MEC systems for H_2 production (Azwar et al., 2014). The factors affecting MEC system performance include medium pH, electrode material, temperature, electrode surface area, solution conductivity, and catalyst type and loading (Waqas et al., 2018). The commercialisation of the MEC system has several drawbacks, such as energy losses from overpotential resistance and ohmic losses, methanogenesis that reduces H_2 production by converting H_2 to methane (CH_4), and the high cost of reactor design and electrode materials (Cheng & Logan, 2007).

2.11.10. Aqueous Phase Reforming (APR)

Aqueous phase reforming (APR) is an innovative technology aimed at producing hydrogen from oxygenated hydrocarbons or carbohydrates derived from renewable biomass sources. Operating at pressures of 25-30 MPa and temperatures between 220-750 °C, APR utilises supported Group VIII metal catalysts, with platinum/alumina being particularly active, alongside nickel-based catalysts for their cost-effectiveness.

APR demonstrates substantial benefits due to its low operational temperatures, which reduce undesirable decomposition reactions and minimise the need for additional reactors compared to traditional steam reforming. The process enables the simultaneous execution of the water-gas shift reaction, producing H_2 and CO_2 while yielding minimal CO emissions. This simplicity in reactor design aligns well with sustainable hydrogen production goals. Research has focused on supported Group VIII catalysts, with Pt/Al_2O_3 being the most active, while nickel-based catalysts remain appealing due to their low cost.

The APR reactions occur at significantly lower temperatures (220–270 °C) than conventional alkane steam reforming (around 600 °C). Because aqueous-phase reforming reactions occur at low temperatures, they reduce the number of undesirable decomposition reactions when carbohydrates are heated to high temperatures. Furthermore, at the same temperatures as APR reactions, the water-gas shift reaction (WGS) is advantageous, allowing for the production of H_2 and $CO_2(g)$ in a single reactor while emitting little CO. To achieve low CO levels in the product gas, typical steam reforming processes require multistage or multiple reactors. Another advantage of the APR process is that it eliminates the need to vaporise water, which saves significant energy when compared to traditional vapor-phase steam reforming processes.

2.11.11. Photoelectrolysis

Photoelectrolysis, while still in its developmental stage, shows promise as an efficient means of generating hydrogen from renewable resources (Burton et al., 2021). This process utilises solar energy to power water splitting, positioning itself as a clean alternative to conventional hydrogen production methods. Pioneering work in 1972 by Honda and Fujishima demonstrated the potential of photoelectrochemical (PEC) water splitting using a titanium dioxide crystal.

The photoelectrode, which fires optimal reactions for oxygen and hydrogen production, encompasses photovoltaic, catalytic, and protective layers. Each component plays a crucial role in maximising efficiency, with required bandgap energies for effective water splitting typically exceeding 2 eV (El-Shafie, Kambara, and Hayakawa, 2019). Selecting appropriate semiconductor materials is vital to achieving high optical absorption, conductivity, and durability against corrosive environments found in aqueous electrolytes.

Photoelectrolysis drives water electrolysis by utilising a photoelectrochemical (PEC) light collection system. Enough electrical energy is generated when a semiconductor photoelectrode is immersed in an aqueous electrolyte and exposed to solar radiation to power the hydrogen and oxygen reactions (Kalamaras & Efstathiou, 2013). Electrons are released into the electrolyte when hydrogen is produced, whereas oxygen production necessitates the release of free electrons. The reaction is influenced by the type of semiconductor material used as well as the solar intensity, resulting in a current density of 10–30 mA/cm^2. The voltage required for electrolysis at these current densities is approximately 1.35 V.

The photoelectrode comprises photovoltaic (semiconductor), catalytic, and protective layers, all of which can be independently modeled. Each layer impacts the overall efficiency of the photoelectrochemical system. The photovoltaic layer is composed of light-absorbing semiconductor materials, with performance proportional to the light absorption of the semiconductor material. Semiconductors with large bandgaps possess the required water-splitting potential. The catalytic layers of the photoelectrochemical cell also affect electrolysis performance which necessitates the use of appropriate water-splitting catalysts. Another critical component of the photoelectrode is the encased layer which prevents the semiconductor from corrosion inside the aqueous electrolyte. This layer must be highly transparent to maximise solar energy absorption by the photovoltaic semiconducting layer (El-Shafie, Kambara and Hayakawa, 2019).

2.12. Working Principle

The working principle of PEC involves converting light energy into electrical energy within a cell containing at least two electrodes immersed in an electrolyte. The ability of the photoanode to absorb light generates electron-hole pairs, facilitating water oxidation and hydrogen production as protons migrate to the cathode, where they are reduced. This method enhances the sustainability and efficiency of hydrogen production, making it a critical area of research in renewable energy technologies.

2.12.1. Thermochemical Water Splitting

Thermochemical water splitting employs high-temperature heat from nuclear or solar power to dissociate water into hydrogen and oxygen. This innovative method leverages a series of thermally driven chemical reactions, leading to efficiencies of up to 50% (Han et al., 2007). While it requires careful management to separate hydrogen from oxygen due to their potential to form an explosive mixture, the promise of a closed-loop system utilising only water and high temperatures provides a compelling avenue for sustainable fuel production.

2.12.2. Sulfur-iodine Thermochemical Water Splitting

The Sulfur-Iodine (SI) thermochemical water-splitting cycle is a promising method for hydrogen production, offering high efficiency and potential scalability. In sulfur-iodine thermochemical cycles, water is decomposed into hydrogen and oxygen at significant temperatures (~850 °C) through sulfuric acid and hydrogen iodide reactions, enabling the continuous recycling of reagents. This self-sustaining process highlights one of the potential pathways for achieving efficient and environmentally friendly hydrogen production without generating disposal waste.

2.12.3. Plasma Reforming

Plasma reforming, an innovative approach utilising electrical energy to create plasma, facilitates hydrogen production through reductive and oxidative reactions. This method's advantages include the elimination of catalysts, compact system designs, and lower operational temperatures. However, drawbacks like electrical demands and electrode degradation at high pressures remain challenges for widespread implementation (El-Shafie, Kambara, and Hayakawa, 2019). Addressing these issues is essential for optimising plasma reforming technologies and ensuring their viability within the hydrogen production landscape.

2.12.4. Ammonia Cracking

Ammonia cracking is emerging as a promising method for hydrogen production. With a high energy density (8.9 kWh/kg) and efficient decomposition into hydrogen and nitrogen, ammonia presents another avenue for clean fuel applications. The ammonia cracking process operates at elevated temperatures (800-900 °C) without the high-pressure requirements of traditional ammonia synthesis (Itoh et al., 2002).

Despite its potential, the sector has seen limited development compared to hydrocarbon reforming pathways. Consequently, further research and investment in ammonia-based hydrogen systems may help catalyse advancements in hydrogen production technologies.

2.12.5. Electrolysis

Water electrolysis can be traced back over two centuries, originating from early experiments in the late 18th century. Notably, Jan Rudolph Deiman, Adriaan Paets van Troostwijk, and J.W. Ritter contributed foundational work to this process, refining methods to produce hydrogen. While the commercial application that initiated in 1890 was significant, water electrolysis still accounts for approximately 4% of global hydrogen production today (Chisholm & Cronin, 2016). According to Chisholm and Cronin (2016), Jan Rudolph Deiman, and Adriaan Paets van Troostwijk were the first to demonstrate water electrolysis using an electrostatic generator in 1789. J.W. Ritter utilised Volta's battery technology to separate the product gases in 1800. Dmitry Lachinov invented an electrolysis method for industrial synthesis of hydrogen and oxygen in 1888. This process produces only about 4% of the world's hydrogen. Water electrolysis, or the separation of water into hydrogen and oxygen, is a well-known method that was commercially used for the first time in 1890. Charles Renard built a water electrolysis unit to produce hydrogen for use in airships, which is further confirmed by Jan Rudolph Deiman, Adriaan Paets van Troostwijk, who were the first to demonstrate water electrolysis using an electrostatic generator in 1789 as confirmed in Kerala (2021).

2.13. The Evolution of Electrolysers

Electrolysers have undergone substantial transformations over the years. Their evolution can be categorised into several generations, each characterised by distinct technological advancements and efficiency improvements.

2.13.1. First Generation Electrolyser (1800-1950)

In this early period, electrolysers were predominantly employed for ammonia synthesis and operated using low-cost electricity sourced from water. By 1900, over 400 industrial electrolysers were in operation, primarily consisting of alkaline systems using concentrated solutions of potassium hydroxide (KOH). Gas separators were often diaphragms made of asbestos, which posed health hazards. Transitioning away from asbestos diaphragm separators (later discovered a health hazard) occurred as an alternative like ZIRFON® zirconium oxide was adopted (Rosa, Santos, & da Silva, 1995). Electrolysers during this era were straightforward and accessible but limited in efficiency. They also produced hydrogen as a by-product from the chlorine production process using concentrated sodium chloride (Santos *et al*., 2013).

During this time, electrolysers were primarily used to produce ammonia using low-cost electricity generated from water. More than 400 industrial electrolysers were in use by 1900. Electrodes were used in countries such as Norway, Peru, Zimbabwe, and Egypt. Alkaline electrolysers were the only type used during this period. The operating conditions included atmospheric pressure and highly corrosive concentrated alkaline solutions such as potassium hydroxide [KOH]. Lonza (later IHT) was the first of the companies to introduce pressurised alkaline electrolyser systems in 1948.

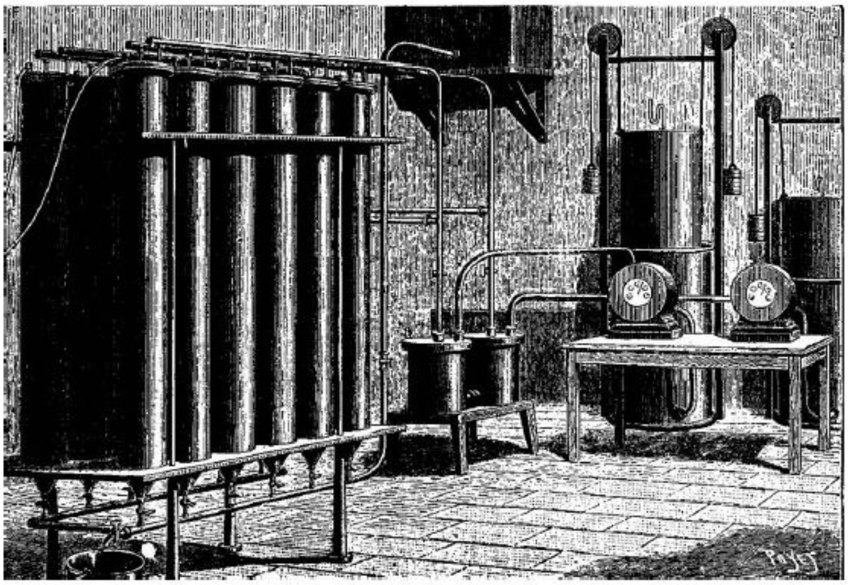


Figure 2.14: Early industrial electrolysis of water plants (Praveen and Sethumadhavan, 2017)

2.13.2. Second Generation Electrolysers (1950-1980)

The introduction of polymer chemistry during this period revolutionised electrolysis. Dupont's discovery of a material with exceptional mechanical and thermal properties led to the development of polymer electrolyte membrane (PEM) electrolysers. These devices marked a transition away from corrosive alkaline solutions, enabling the use of pure water and resulting in simpler systems with higher efficiencies. Notable advancements made by companies, including General Electric, laid the groundwork for PEM technology adaptation (IRENA, 2020).

The breakthrough in polymer chemistry defined this generation of electrolysers and was a game changer. In 1940, Dupont discovered a material with excellent mechanical and thermal stability and ionic properties, facilitating the transition from diaphragms to membranes. PEM electrolysers were created following this discovery. A PEM cell uses pure water instead of the corrosive caustic solutions commonly utilised in alkaline electrolysers resulting in significant reductions in system complexity while providing higher efficiencies. General Electric pioneered the development of PEM electrolysers, followed by Hamilton Sundstrand in the United States, Siemens in Germany, and ABB in Switzerland (IRENA, 2020).

2.13.3. Third Generation Electrolysers (1980-2010)

Following the conclusion of the space race, improvements in PEM technology focused on simplifying designs, reducing costs, and enhancing cell capacities to a few hundred kW. This generation of electrolysers achieved significant efficiency gains while extending service lifetimes to over 50,000 hours. Transformations involved pressurising alkaline electrolyser units into smaller, more compact designs, permitting applications with varying hydrogen demand (Hickner et al., 2004).

Once the space race concluded, alternative uses for PEM electrolysers needed to be identified. This process necessitated drastically simplifying the design while simultaneously reducing the costs of cell stacks and increasing their capacities to a few hundred kW. These adaptations increased overall system efficiency and durability exceeding 50,000 hours. Large alkaline electrolyser units had to be redesigned into pressurised and significantly smaller stacks, allowing for usage in environments with lower hydrogen demand and production requirements (Hickner et al., 2004).

2.13.4. Fourth Generation Electrolysers (2010-2020)

Increased interest in hydrogen as a substitute for fossil fuels characterized this generation. External pressures, such as the need to reduce carbon emissions, spurred the integration of renewable energy sources (e.g., solar and wind) into electrolyser designs (Brauns & Turek, 2020). While the costs of electrolysers showed modest reductions, ongoing advancements in electrode materials and metal catalysts consistently improved performance metrics, addressing economic viability for green hydrogen production (Li & Baek, 2021; Wagner et al., 2023).

This generation has seen a surge of interest in electrolysers as hydrogen gains traction as a potential substitute for fossil-based fuels. The impetus to reduce carbon emissions in combating climate change has also bolstered the evolution of hydrogen electrolysers. As a result, electrolysers have adapted to accommodate renewable energy sources such as solar and wind (Brauns & Turek, 2020). The cost of electrolysers has decreased slightly, but efficiency continues to improve as the electrode materials and metal catalysts are regularly modified (Li & Baek, 2021; Wagner et al., 2023).

Electricity remains the most expensive component of green hydrogen production. Accessing lower-cost power will substantially reduce the cost of green hydrogen products, improving their economic viability. Green hydrogen has also become a matter of political interest, with countries advocating policies that discourage fossil fuel use in favor of those that support renewable energy dynamics (Bazilian et al., 2012).

2.13.5. Fifth Generation Electrolysers (Post-2020)

This phase aims for mass hydrogen production using electrolyser scales from megawatts (MW) to gigawatts (GW). The goals for this generation include further lowering electrolyser costs, extending operational lifetimes beyond 50,000 hours, and achieving efficiencies exceeding 90%. The realisation of these targets will depend on leveraging economies of scale alongside innovations in manufacturing and research (Hydrogen Council, 2020).

This period is expected to usher hydrogen electrolysis into widespread use, scaling up from MW to GW capacities, and turning potential into reality. The goals for this stage include reducing electrolyser costs, ensuring a longer lifetime (i.e., greater than 50,000 hours), and improving efficiency beyond 90%. Realising this requires economies of scale, enhanced manufacturing capacities, and technological breakthroughs derived from research and innovation (Hydrogen Council, 2020).

2.14. The Principle of Water Electrolysis

Pure water is generally a poor electrolyte, necessitating additional energy in overpotential to facilitate the electrolysis process. Due to water's limited self-ionization, achieving efficient electrolysis without added electrolytes, such as salts, acids, or bases, would result in abysmally slow reaction rates. Common electrolytes include KOH and NaOH, which enhance conductivity and promote effective ion transport (Kumar & Himabindu, 2019).

During electrolysis, a direct current (DC) source is connected to two electrodes, a positive anode and a negative cathode, typically crafted from inert metals like platinum or iridium. This electrical setup enables the decomposition of water into hydrogen and oxygen at the respective electrodes. Hydrogen ions (H^+) migrate toward the negatively charged cathode, while oxygen ions (O^{2-}) collect at the positively charged anode.

Due to their respective half-reactions, the reaction produces hydrogen and oxygen in a 2:1 molar ratio in an ideal scenario. Maintaining high Faradaic efficiency is crucial for optimal performance, as it reflects the fraction of charge used for the desired reactions compared to side reactions or losses. High Faradaic efficiency indicates that most of the electrical energy is being converted into the target products (hydrogen and oxygen) without significant losses due to competing reactions, which often complicate the ideal situation.

Pure water's inefficacy as an electrolyte necessitates applying additional energy, known as overpotential, to overcome ionization barriers. If sufficient power is not applied, pure water undergoes electrolysis at a prolonged rate, primarily due to its limited self-ionization properties. Pure water has an electrical conductivity of about one millionth that of seawater. An electrolyte, such as a salt, alkali, or acid, is added to the pure water to improve the efficiency of the electrolytic process (Kumar & Himabindu, 2019).

Water electrolysis is the process of converting water into oxygen and hydrogen gas using electrical energy. The hydrogen gas produced can be used as hydrogen fuel in fuel cells for heating, cooking, and hydrogen-powered vehicles. Oxygen can be purified further and used in hospitals or other industries for welding, among other applications (Levie, 1999). To decompose water, a direct current (DC) electrical power source is connected to two positive and negative electrodes. Typically, the electrodes are made of an inert metal such as platinum or iridium. The electrodes are placed in water to introduce current, facilitating the ionization of the water. Hydrogen will form at the negatively charged cathode since hydrogen ions have a positive charge (opposite charges attract), while oxygen will form at the positively charged anode due to oxygen having a negative charge. If the process operates at Faradaic efficiency, the total volume of hydrogen gas produced at the cathode should be twice that of oxygen produced at the anode. The products at the electrodes are also proportional to the total electrical charge that has passed through the electrolyte. However, because various competing reactions can occur in the solution, Faraday's law may not hold for several reactions (Carmo & Fritz, 2013).

- **2.15. Thermodynamics of Water Electrolysis**
- **Anode Reaction** (Oxidation): [2H_2O \rightarrow O_2 + 4H^+ + 4e^-]
- **Cathode Reaction** (Reduction): [4H^+ + 4e^- \rightarrow 2H_2]

The overall cell reaction is: [2H_2O \rightarrow 2H_2 + O_2]

2.15. Thermodynamics of Water Electrolysis

The thermodynamics of water electrolysis reveal the inherent challenges involved in breaking down pure water into hydrogen and oxygen. Under standard conditions, this process is generally thermodynamically unfavorable. Specifically, the overall electrochemical reactions can be represented by two half-cell reactions at standard conditions, with a standard cell potential of approximately +1.23 V at 25 °C in neutral conditions (pH 7)(Colli, 2019).

- **Anode and Cathode Reactions**

The reactions occurring at the anode and cathode can be described as follows:

Anode Reaction:

$$2H2O(l) \rightarrow O2(g) + 4H + (aq) + 4e^{-}$$

$E_O = +1.23V$ (For the reduction half-equation)

Cathode Reaction:

$$2H + (aq) + 2e^{-} \rightarrow H2(g)$$

Due to various factors such as diffusion resistance, electrical resistance in wires, and the formation of gas bubbles, electrolysis requires an applied potential greater than the theoretical limit to overcome activation barriers. This additional potential is referred to as **overpotential**.

- **Nernst Equation**

To establish the relationship governing the cell potential, the **Nernst equation** can be applied. At pH 0, where the concentration of hydrogen ions ($[H^+]$) is 1.0 M, the standard cell potential (E°_{cell}) is approximately -1.229 V. Conversely, at neutral pH 7, the concentration of hydrogen ions is 1.0×10^{-7} M, which affects the cell potential.

The Nernst equation helps us adjust the standard potential to account for these concentrations:

$$E = E^\circ - \frac{RT}{nF} \ln Q$$

Where:

- (E) = measured potential
- (E°) = standard cell potential
- (R) = universal gas constant (8.314 J/mol·K)
- (T) = absolute temperature (K)
- (n) = number of moles of electrons exchanged
- (F) = Faraday constant (96,485 C/mol)
- (Q) = reaction quotient

- **Standard Free Energy Changes**

To further examine the thermodynamics involved in electrolysis, standard-state free energy (G°) can be calculated using:

$$G^\circ = n F E^\circ$$

In the reaction of two water molecules, the stoichiometry indicates that four electrons are transferred ($n = 4$). The free energy change (ΔG°), enthalpy change (ΔH°), and entropy change (ΔS°) can be summarized as follows:

- ($\Delta G^\circ = 474.48$) kJ / 2 mol of water = 237.24 kJ/mol of water
- ($\Delta S^\circ = 163$) J/(K·mol of water)

- (ΔH° = 571.66) kJ / 2 mol of water = 285.83 kJ/mol of water

This results in a specific energy requirement of approximately 141.86 MJ/kg of hydrogen produced.

Overall, while the theoretical potential may indicate that water electrolysis can occur under standard conditions, the practical application of this process often encounters significant hurdles necessitating higher applied potentials due to intrinsic factors such as high activation energy, ion mobility, and concentration gradients (Colli, 2019).

2.16. Electrolysers

An electrolytic cell employs electrical energy to incite redox reactions that do not spontaneously occur. Often, water decomposition into hydrogen and oxygen is a paramount example. Each electrolytic cell comprises three fundamental components:

- Electrolyte
- Two electrodes
- Power source

While traditionally only four types of electrolysers are often mentioned (alkaline, polymer electrolyte membrane (PEM), solid oxide electrolysis cells (SOEC), and anion exchange membrane electrolysis (AEM)), the field has expanded to encompass additional configurations and specialised designs tailored to various application needs (IRENA, 2020; Burton et al., 2021). Understanding these electrolysis systems is critical for this study because it establishes a foundation for evaluating their performance and economic viability in renewable energy applications, particularly hydrogen innovations. By examining these advancements in both electrolysis methods and catalyst materials, this study aims to provide insights into how innovations can enhance the efficiency and cost-effectiveness of water electrolysis, thus supporting the broader shift towards sustainable hydrogen production. The overall comparison of the four types of electrolysers discussed above is summarised in Table 2.4 below.

Table 2.4: Comparison of Electrolyser Types (Source: IRENA, 2020)

	Alkaline	PEM	AEM	Solid Oxide
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 molL^{-1}	PFSA membranes	DVB polymer support with KOH or NaHCO3 1molL^{-1}	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (*e.g.* LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

2.17. Electrocatalysts

While the theoretical cell potential for water electrolysis is set at 1.23 V, achieving this requires overcoming activation barriers rather than merely addressing ohmic losses. Electrocatalysts facilitate electrode reactions, crucial for both the anode (oxygen evolution) and cathode (hydrogen evolution), thus reducing the activation energy necessary for these reactions. Noble metals such as platinum and iridium are typically employed as catalysts, adding to the operational costs of PEM and alkaline systems.

To lower the financial overhead of AEM technology, research into more readily available catalysts is imperative. Emerging candidates like nickel, nickel-iron alloys, and graphene are being evaluated for their performance in harsh electrolytic environments (Vincent & Bessarabov, 2017; Henkensmeier et al., 2021).

2.17.1. Alkaline Electrolysis

Alkaline electrolysers feature a relatively simple stack design, utilizing a highly concentrated KOH solution as the electrolyte (Figure 2.15). The electrodes, often stainless steel coated with nickel, leverage hydroxyl ions (OH^-) as the charge carriers (Sanchis & IEEE, 2012). Notably, alkaline designs are recognized for their durability, with lifespans extending beyond 30 years, underscoring their maturity and reliability in commercial hydrogen production.

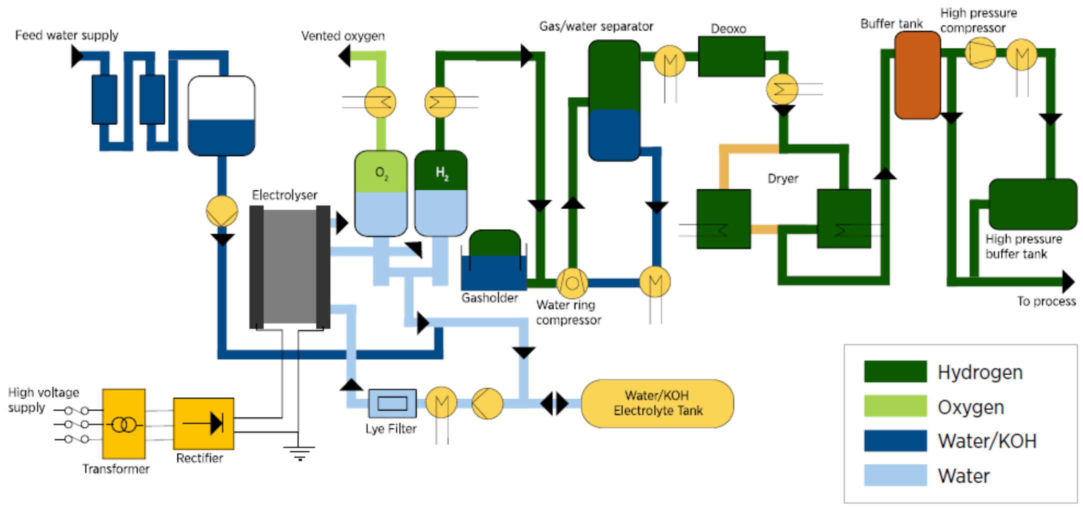


Figure 2.15: System level of an alkaline electrolyser (IRENA, 2020).

2.17.1.1. Cell Level

Two types of water electrolysis cells can be used in alkaline electrolysers. These are namely tank cells (unipolar configuration) and filter-press cells (bipolar configuration) (Figures 2.16 & 2.17).

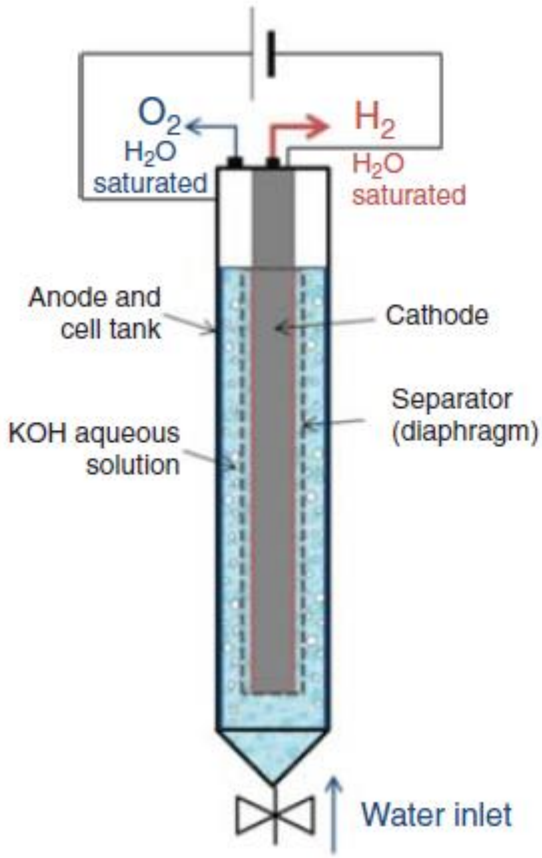


Figure 2.16: An example of a tank cell alkaline electrolyser (Guillet and Millet, 2015)

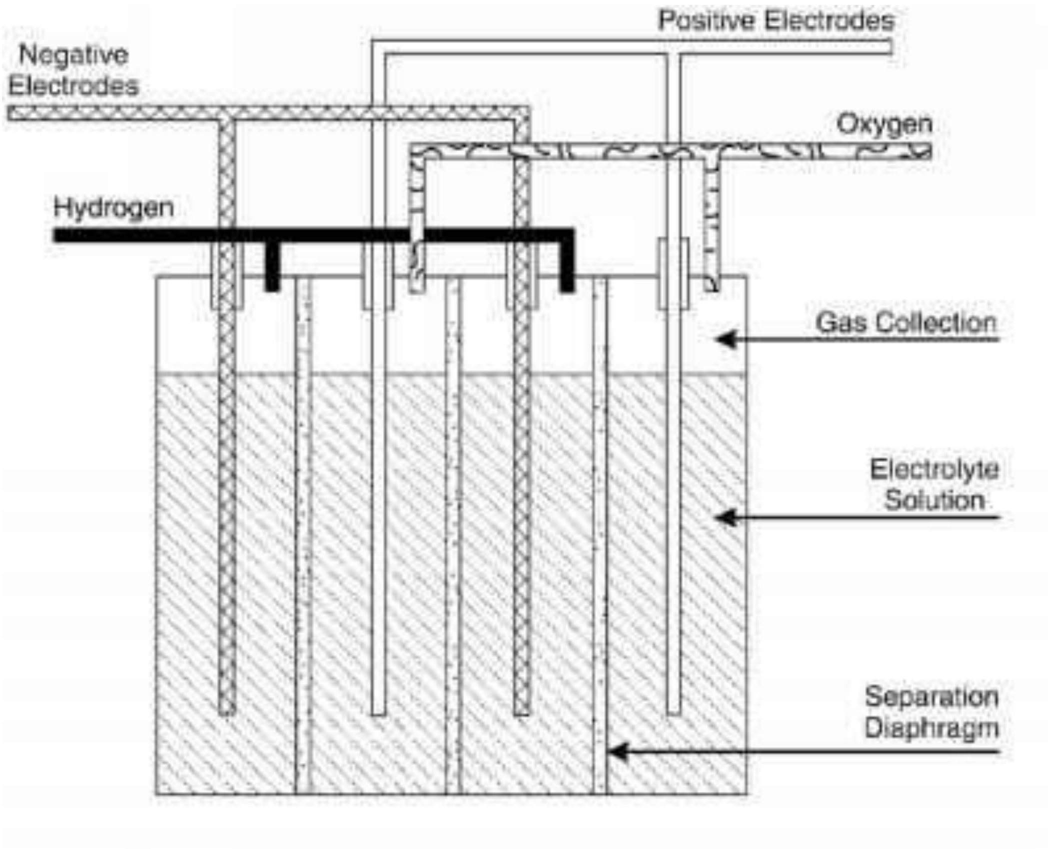


Figure 2.17: An example of a filter-press alkaline electrolyser (Williams, 2022).

These designs feature significant structural differences, with the bipolar configuration potentially providing higher efficiency by reducing energy losses at the expense of more complex construction requirements. The operating current density of industrial alkaline water electrolysers is typically 10–20% of the rated power. This limitation arises because the porous material separating the two compartments (oxygen and hydrogen) is slightly permeable to the reaction products, causing gases to dissolve in the electrolyte and vice versa. Consequently, some hydrogen gas may diffuse continuously through the gas separator from the cathodic side to the anodic side, resulting in a mixture of hydrogen and oxygen.

Fick's law of diffusion states that the movement of particles from a high to a low concentration is directly proportional to the concentration gradient of those particles (Adolph Fick, 1855).

2.17.1.2. Fick's Law of Diffusion

- Where J = diffusion flux (amount of substance flowing per unit area)
- D = diffusion coefficient
- φ = concentration or amount of substance per unit volume
- x = distance in cm

If the operating pressure and temperature remain constant the rate of diffusion remains constant. As small amounts of hydrogen and oxygen are produced at each electrode at low current density, constant gas crossover occurs through the separator, diluting purity levels and posing a safety hazard due to the volatility of those mixtures. The lower explosion limit (LEL) for hydrogen in oxygen is 3.9 mol percent, while the upper explosion limit (UEL) is 95.8 percent. Outside of these limits, hydrogen-oxygen mixtures are not flammable. Therefore, caution must be exercised to avoid exceeding these parameters.

A sudden change in current, such as a rapid increase, can result in an extremely high rate of gas production leading to pressure buildup in alkaline cells. When electrodes are immersed in the electrolyte, negative effects similar to those observed in alkaline water electrolysis manifest when sudden current changes are applied. A rapid rise in current may produce an excessive amount of gas quickly, leading to an expulsion of the electrolyte from the compartment and a risk of system destruction. Generally, extreme caution should be exercised in managing operating conditions (Rashid et al., 2015).

2.17.1.3. The Electrolyte and Electrodes

The gap between electrodes is critical in defining the electrolyte volume within the electrochemical cells. NaOH and KOH are strong choices for electrolytes, with KOH favored due to its superior conductivity, which peaks around 30% concentration. Regular maintenance of the electrolyte is essential to address potential impurities that may arise from the corrosion of the system components (Arian & Varkaraki, n.d).

2.17.1.4. Electrolyte options: Electrodes and Catalysts

Any electrochemical electrode material for electrolysis should be corrosion-resistant and exhibit relatively high electrical conductivity. To facilitate the redox reactions occurring at the electrodes, the electrode should also possess high catalytic activity. While stainless steel and lead oxide are less expensive electrode materials for alkaline electrolysis, their chemical stability suffers at high voltages and in highly concentrated alkaline solutions. Consequently, nickel has been adopted for some electrolysers as it exhibits greater corrosion resistance even in highly concentrated alkaline solutions. Nickel also demonstrates relatively high electrochemical activity and is relatively inexpensive. However, one disadvantage is during power outages, nickel electrodes can corrode more swiftly. To enhance the surface area for electrochemical processes, a porous layer of nickel is coated over steel or nickel electrodes. Raney patented the production of high surface area nickel, commonly referred to as "Raney nickel" that was produced by melting nickel with other elements, cooling, pulverizing, and activating with sodium hydroxide. His initial catalyst had a 1:1 ratio of these two components, but variations of this ratio have since emerged (Yang & Lee). The addition of aluminum to the process improved it in 1927.

Other variants of Raney nickel have been produced by mixing nickel with aluminum rather than silicon. This catalyst is prepared by dissolving nickel in molten aluminum, followed by quenching (rapid cooling). During quenching, small amounts of other metals, such as chromium, can be added to enhance catalytic activity. After cooling, the catalyst is pulverized (ground into a powder) and activated by reacting with sodium hydroxide to form sodium aluminate. The leaching process, a reaction with the alkali, requires a very high concentration of sodium hydroxide to prevent forming aluminum hydroxide, which would precipitate as bayerite: Al(OH)3. Temperatures between 70 - 100 °C, as well as sodium concentrations as high as 5M, are employed. The temperature used during the leaching process affects the properties of the catalyst. This catalyst type was used in alkaline water electrolysers until the late 1950s (Nishimura, 1957).

Monometallic oxide catalysts have also emerged as viable options, particularly for anodic reactions. These include nickel and cobalt oxides, improved by incorporating other metallic ions to enhance catalytic activity. The highest catalytic activities are found in oxides containing Ni, Fe, and a third element such as Cr, Al, Ga, or Ca. Mild steel is one of the most common materials used for cathodic electrodes. To improve catalytic activity, nickel and Raney nickel are sometimes deposited on steel plates. A nickel–sulfur alloy, which performs exceptionally well, can also be utilised as a cathode electrode. However, the drawback of this electrode is that it gradually dissolves when the electrolyser is stopped, resulting in a loss of activity. Catalysts composed of metal hydrides have also been studied. During power outages, these catalysts emit small amounts of hydrogen, preventing corrosion.

2.17.2. PEM Electrolyser

PEM technology emerged during the space race, pioneered by General Electric, focusing on operating under conditions where liquid-based electrolysers were impractical. PEM electrolysers facilitate efficient proton conduction and can adapt to acidic media, improving performance compared to their alkaline counterparts. Although their initial costs are high, their efficiency in hydrogen production at significant current densities positions PEM electrolysis as a promising avenue for green hydrogen applications (Doenitz et al., 1980; Carmo & Fritz, 2013).

2.17.3. PEM Cell Level

The compact design of PEM electrolysers integrates a solid electrolyte membrane that facilitates proton conduction while separating produced gases. This structure enables enhanced current densities and operational efficiencies, positioning PEM technology as a critical element for advancements in hydrogen fuel technology. The PEM cell is illustrated in Figure 2.18 below.

- **Anodic reaction :**

$$H_2O(l) \rightarrow {}^{1}/_{2}\, O_2(g) + 2H^+ + 2e^-$$

- **Cathodic reaction :**

$$2H^{+} + 2e^{-} \rightarrow H_2(g)$$

- **Overall reaction :**

$$H_2O(l) \rightarrow H_2(g) + {}^{1}/_{2}\, O_2(g)$$

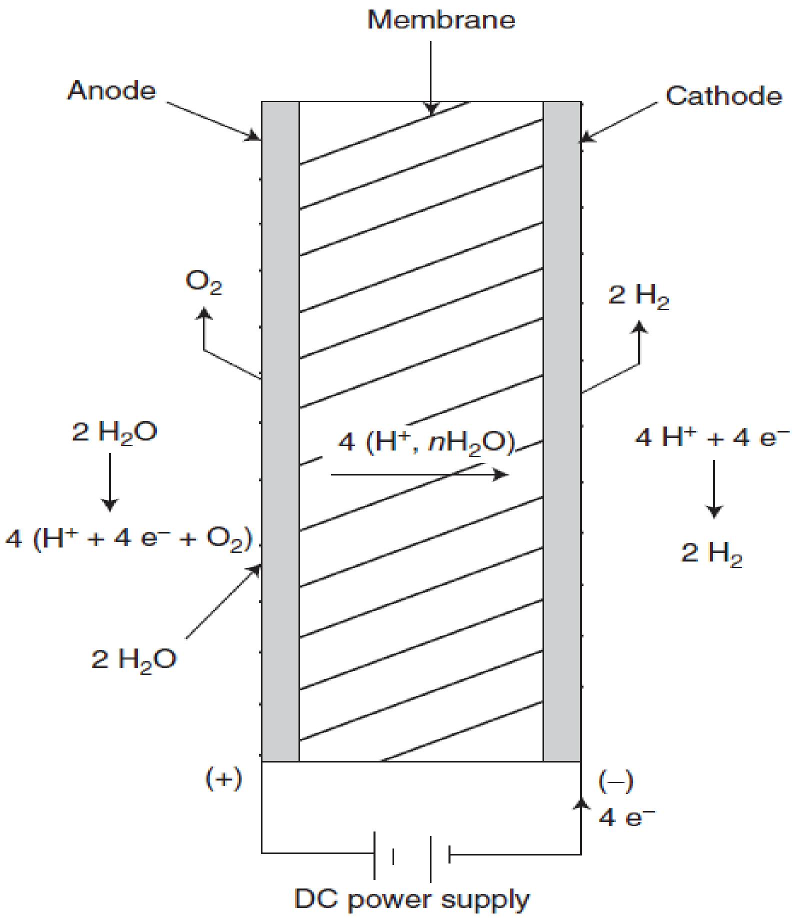


Figure 2.18: The PEM cell (Godula-Jopek n.d.)

2.17.3.1. Cell Stack level

The PEM cell stack consists of several integral parts. It includes a membrane–electrodes assembly (MEA) made of polymer membranes, with electrocatalysts coated on both sides of the membranes. The MEA is sandwiched between two porous titanium particle-based current distributors. Electrical current is introduced into the cells via two hollow bipolar plates, which also serve as a barrier between adjacent cells. Water enters the anode via channels which also collect gases in each cell compartment. Points of contact between current collectors and electrocatalytic layers must be small enough to ensure good current distribution at interfaces. The end plates are powered by an external DC supply and gaskets are also required to seal the cells. Figure 2.19 depicts a cross-section of the PEM cell stack.

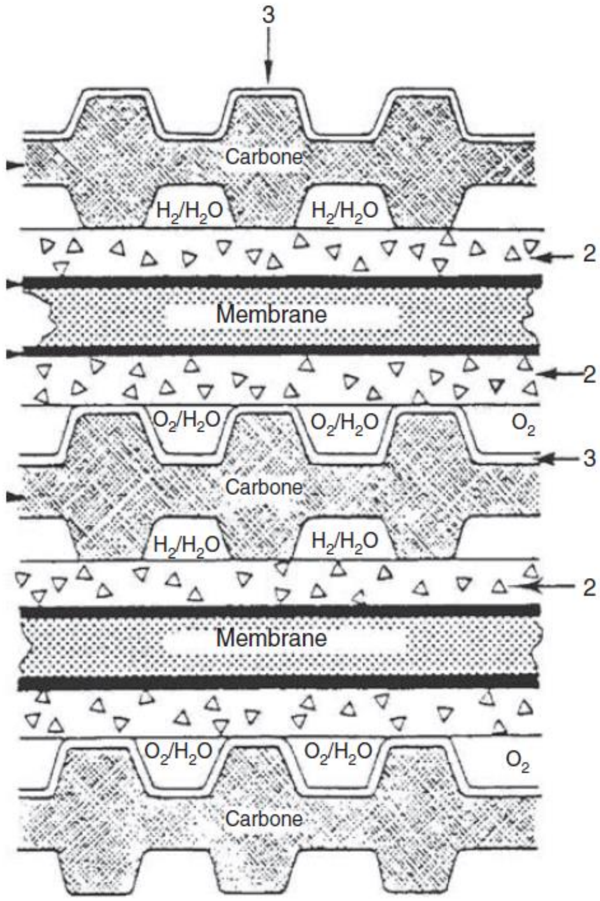


Figure 2.19: Cross section of a PEM Cell Stack (Godula-Jopek n.d.)

Cells are stacked together to increase production capacity because individual cells have lower capacities. The two primary methods for stacking cells are parallel and series stacking. These connections can be utilised in various configurations, including monopolar and bipolar cell stacking. The various stacking types ensure uniform distribution and efficient collection of water and gaseous products. To avoid current fluctuations within cells, an even current distribution is paramount. Sealants are also employed to ensure uniform compressional force distribution and to adjust individual cell volume. Cell stacks may either be mounted in pressurised chambers or fitted into cylinders. Two high-pressure pumps are used to circulate liquid between the anode and cathode compartments. As shown in Figure 2.20, system-level designs should ensure uniform distribution of liquid and current across the cell compartments.

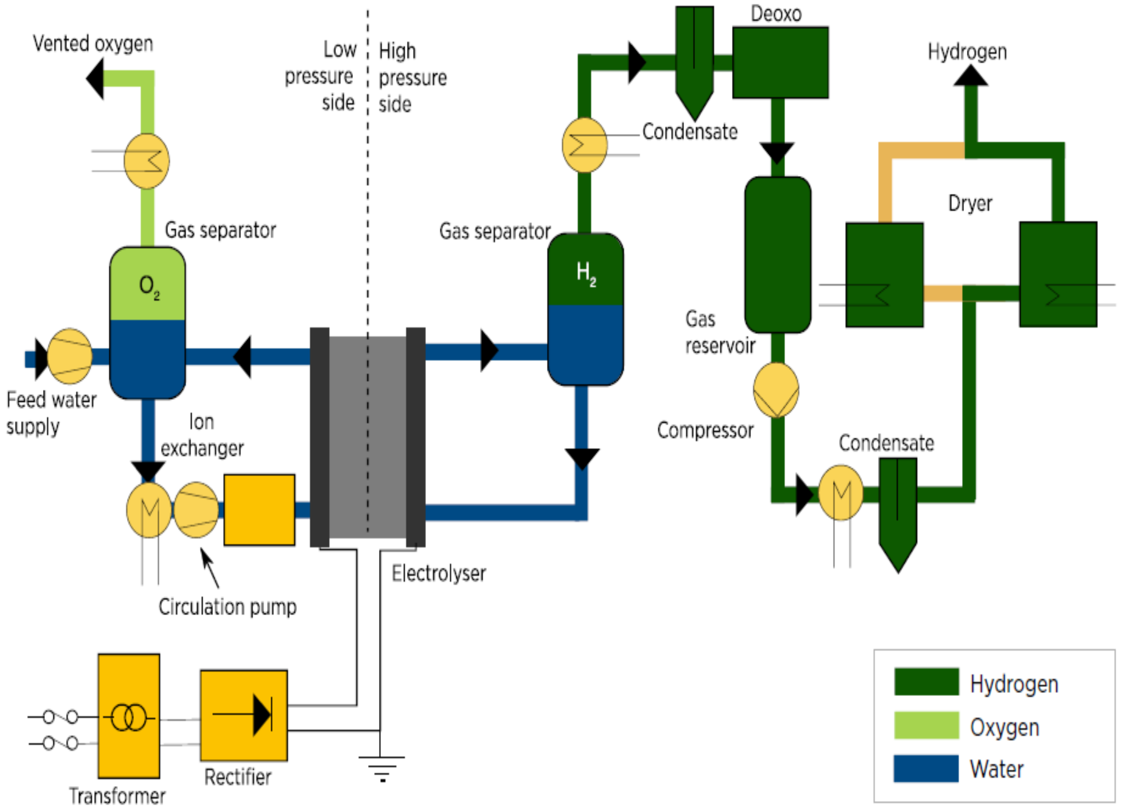


Figure 2.20: System level of PEM electrolyser (IRENA, 2020).

2.17.4. Solid Oxide Electrolyser Cell (SOEC)

SOEC technology offers an efficient alternative for hydrogen production, especially at elevated temperatures (500-850 °C), allowing for reduced energy expenditure in the water-splitting process. With ongoing research for improving the durability of ceramic materials, SOEC technology has great potential for greater commercial scalability in hydrogen production (Donitz & Erdle, 1985; Carmo & Fritz, 2013).

2.17.4.1. Operating Principle

A solid electrolyte is utilised in SOEC electrolysers. It operates at temperatures ranging from 500 to 850 °C. Water is split into hydrogen and oxygen at the respective electrodes, with steam introduced into the porous cathode. Steam diffuses to the cathode-electrolyte interface, where reduction occurs, producing hydrogen gas and oxygen ions.

The produced hydrogen diffuses up through the cathode and collects at its surface, while the oxygen ions are carried through the dense electrolyte. The electrolyte should be dense enough to prevent hydrogen and steam diffusion as this would result in the recombination of hydrogen and oxygen to reform water. At the electrolyte-anode interface, oxygen ions are oxidized with oxygen gas and collected. The reactions at each electrode are as follows:

- Anode reaction:

$$2O_2\text{-} \rightarrow O_2 + 4^{e^-}$$

- Cathode reaction:

$$H_2O + 2e^- \rightarrow H_2 + O_2\text{-}$$

- Overall reaction:

$$2H_2O \rightarrow 2H_2 + O_2$$

2.17.4.2. Cell Level

The cathode and anode of a solid oxide electrolysis cell (SOEC) are constituted of ceramic layers, an electrolyte, and two porous electrodes. The cell is made of ceramics due to the high operating temperatures. Ceramics are materials that exhibit extreme hardness, brittleness, heat resistance, and corrosion resistance. The most common electrolyte is a dense ionic conductor composed of ZrO_2 doped with 8 mol percent Y_2O_3. The main reasons for employing zirconia dioxide include its high strength, melting point (around 2700 °C), and high corrosion resistance. The inclusion of Y_2O_3 modifies the physical properties of ZrO_2, preventing rapid cooling, which can lead to cracking and scattering of the electrolyte. Alternatives for electrolyte materials include scandia-stabilised zirconia (ScSZ), ceria-based electrolytes, and lanthanum gallate materials.

2.17.4.3. Electrode Material for the Cathode

The most widely used cathode electrode material is Ni-doped Yttria-stabilized zirconia (YSZ). Electrodes degrade catalytically over time due to nickel oxidation at the Ni-YSZ interface resulting from high steam partial pressures. Alternatively, lanthanum strontium manganese (LSM) perovskite may serve as a cathode material. Research has indicated that doping LSM with scandium improves electrode performance at lower temperatures by enhancing oxide ion mobility within the cathode. Nonetheless, precipitated scandium oxide in the LSM lattice may obstruct electron and ion movement within the cell. New materials, such as lanthanum strontium manganese chromate (LSCM) are also being investigated for improved chemical stability (Laguna-Bercero).

2.17.4.4. Anode Electrode Material

Lanthanum strontium manganite (LSMO) is the most utilised anode material. LSMO has demonstrated exceptional performance. Infusing LSMO electrodes with nanoparticles extends cell life by preventing delamination at the electrode/electrolyte interface. A study from 2010 discovered that incorporating neodymium nickelate into a SOEC electrolyser operating at 700 °C increased current density nearly twice that of conventional LSMO anode material. When the SOEC electrolyser operated at 800 °C, the increase was roughly four times the current density. The improved performance was attributable to the material's higher stoichiometric oxygen quantities, enhancing ion conduction.

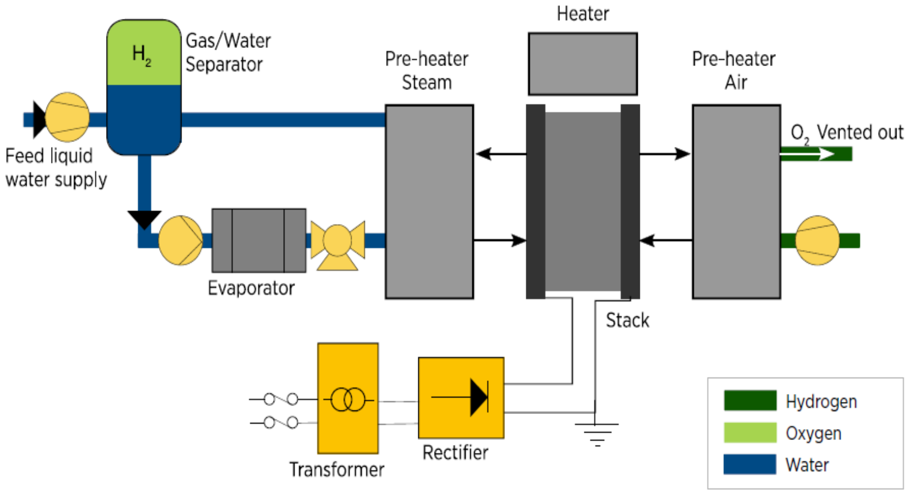


Figure 2.21: System level of a SOEC Electrolyser (IRENA 2020).

2.17.5. AEM Electrolysis

AEM technology merges the advantages of PEM and alkaline systems, enabling the use of non-noble catalysts while maintaining comparable efficiency levels. However, the lack of commercially viable membranes presents challenges that necessitate further exploration in this burgeoning field.

2.17.5.1. Operating Principle

AEM electrolysis is the electrochemical decomposition of water into hydrogen using an Anion Exchange Membrane (AEM). As suggested by the name, an anion exchange membrane is a partially permeable membrane that restricts the movement of some ions while allowing others to pass through. The membrane used for electrolysis is typically made of ionomers that facilitate ion conduction, usually gases like oxygen or hydrogen (Vincent et al., 2017; Kruger et al., 2017; Bessarabov et al., 2017). A schematic of an AEM electrolyser is depicted in Figure 2.22.

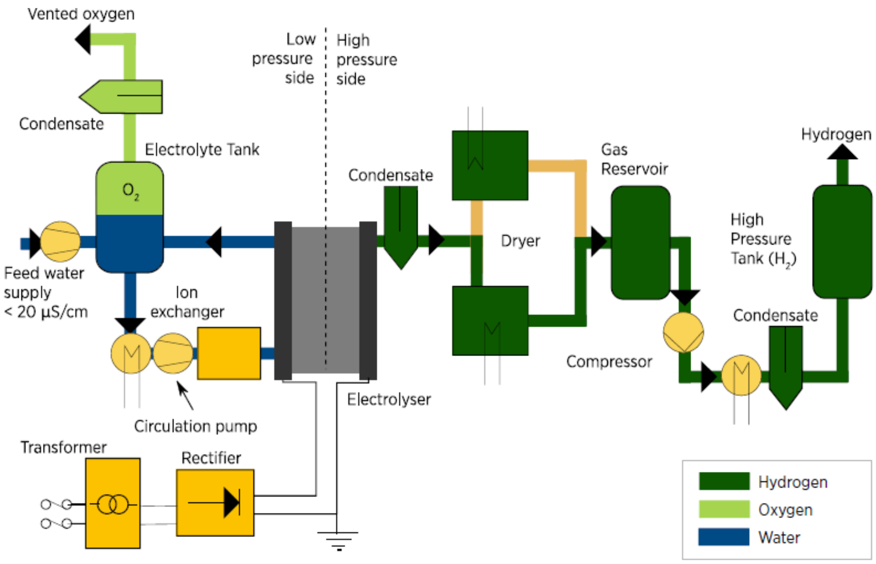


Figure 2.22: System level for AEM electrolyser (IRENA, 2020).

2.17.5.2. Cell Level

The cell consists of an anode, a cathode, and a membrane as illustrated in Figure 2.23.

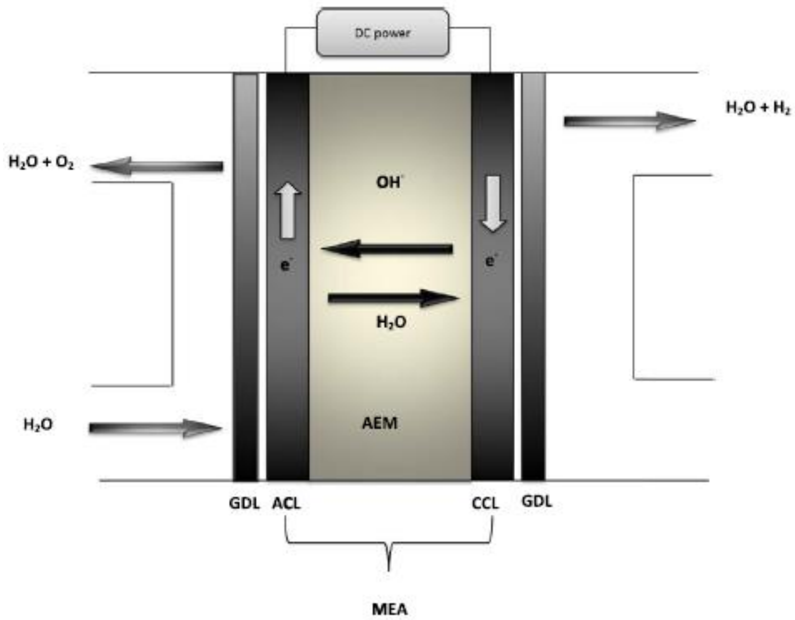


Figure 2.23: AEM electrolytic cell (Vincent and Bessarabov, 2017)

The membrane, together with the electrodes, forms the Membrane Electrode Assembly (MEA), which serves as the electrolyser's heart. An ion exchange membrane, an ionomer, and electrodes coated with catalysts namely, the cathode catalytic layer (CCL) and the anode catalytic layer (ACL), comprise the membrane electrode assembly. The electrodes are subsequently connected to a DC power source, with a separate gas diffusion layer present on each electrode side (GDL). The subsequent half-cell reactions occur:

Anode Reaction:

$$4OH^- \rightarrow O_2 + H_2O + 4e^- \quad E = 0.401V$$

Cathode Reaction:

$$4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \quad E = -0.828V$$

Overall Reaction:

$$2H_2O \rightarrow 2H_2 + O_2 \quad E = 1.23V$$

At 25 °C, the reaction requires 1.23 V to decompose water into hydrogen and oxygen. In practice, the reaction requires more than 1.23 V to occur efficiently. However, overpotential is also necessary to overcome the ohmic resistance of the electrolytes.

2.17.6. Ion Exchange Membranes

The ion exchange membrane employed in an AEM electrolyser substantially impacts its performance. An anion exchange membrane is typically composed of a polymer backbone linked to an anion exchange functional group. Polysulfone (PSF) is commonly used as the polymer backbone and is cross-linked with divinylbenzene (DVB), though polystyrene can also be utilised. These polymers are combined with ion exchange groups like –NH, –R2N, –NH3, –RNH_2 or ammonium salts. An effective and efficient ion exchange membrane should be stable under the electrolyser's varying chemical conditions, possess mechanical strength, and be thermally stable while ensuring high ionic conductivity. It should also be impermeable to hydrogen and oxygen to prevent mixing.

The polymer backbone substantially impacts thermal stability and mechanical strength. The ion exchange groups of the polymer backbone determine ionic conductivity, influencing the membrane's ability to exchange ions. The membrane's chemical stability is dictated by both the polymer backbone and the functional groups. An excess of ion exchange groups can be added to the polymer to enhance ionic conductivity, but this may inhibit the mechanical stability of the membrane due to increased water uptake. The membrane is also susceptible to degradation of ammonium groups due to organic substitution reactions, which can reduce conductivity due to modifications of the ionic groups. Fabrication of a membrane achieving both high mechanical stability and high ionic conductivity remains a challenge, thus highlighting the limitations of AEM in hydrogen mass production (Miller et al., 2020).

2.18. Significance of Unpacking Electrolysis Methods and Electrolysers

The explicit significance of providing a comprehensive overview of electrolysis methods within this study was to contextualise various hydrogen production technologies concerning their efficiency, sustainability, and relevance to future energy systems. The general description of electrolysis methods unpacked in this section promoted several key points in order to:

- ***Highlight the Significance of Hydrogen as an Energy Carrier:*** Hydrogen has emerged as a critical alternative energy carrier, particularly in light of reducing carbon emissions and transitioning from fossil fuels in the quest for sustainable energy solutions. Understanding the electrolysis methods aids in appreciating hydrogen's role in achieving decarbonisation goals.
- ***Assess the Efficiency and Economic Viability of Production:*** By detailing various electrolysis technologies and their respective advantages and limitations, the study evaluates how these methods contribute to the overall efficiency of hydrogen production. This evaluation assisted in identifying pathways to reduce production costs, which serve as a significant barrier to the widespread adoption of hydrogen energy.
- ***Identify Technological Innovations and Future Directions:*** The examination of the evolution of electrolysis technologies, from historical methods to modern advancements, provided insights regarding ongoing trends and areas of innovation, such as AEM and SOEC technologies. Through these insights, the study discussed emerging solutions and their potential for scaling up hydrogen production.
- ***Provide a Basis for Comparison:*** By outlining various electrolysis methods, the study established a framework for comparing these technologies to others in hydrogen production, such as thermochemical and biological approaches. This comprehensive overview allowed for a nuanced understanding of the role of electrolysis within the broader hydrogen production landscape.
- ***Inform Policy and Investment Decisions:*** A thorough understanding of the different electrolysis methods and their capabilities equips policymakers and investors with valuable insights focused on advancing hydrogen technologies. Identifying successful strategies and areas requiring more research can shape funding initiatives and regulatory frameworks that facilitate the expansive growth of the hydrogen economy.

Through elucidating these aspects, the discussion of electrolysis methods ultimately informed stakeholders about the critical role of electrolysis in developing a sustainable hydrogen economy, highlighting potential pathways and challenges that impact the realization of this vision.

2.19. Hydrogen Storage Mechanisms

The various hydrogen storage methodologies explored encompass compressed, liquid, and chemical storage. Understanding these techniques was vital for the practical hydrogen use across sectors.

Hydrogen storage technologies have advanced significantly in recent years. Depending on the hydrogen form requiring storage, diverse methodologies exist. Hydrogen storage technologies are vital in understanding hydrogen's potential in energy systems, addressing crucial storage challenges, and facilitating the transition to a hydrogen economy. Efficient and safe hydrogen storage informs its potential applications in sectors such as transportation, industrial processes, heating, and energy generation. Understanding various hydrogen storage methods including chemical (converting hydrogen into another chemical form) and physical storage (storing hydrogen in its form, either compressed or liquefied)—is critical for optimizing hydrogen's role in maintaining a sustainable energy future (Hirscher et al., 2020).

2.19.1. Liquid Hydrogen Storage

Liquid hydrogen (LH_2) storage plays a pivotal role in hydrogen infrastructure due to its high volumetric energy density compared to gaseous forms. Liquid hydrogen is stored in cryogenic tanks maintained at extremely low temperatures of −251.95°C and at atmospheric pressure. The design and shape of these tanks significantly influence structural integrity and operational safety. Consequently, cylindrical tanks are the predominant choice for liquid hydrogen storage due to their efficiency in managing internal pressures and spatial efficiency. Spherical tanks, while capable, require robust support systems to manage the stresses associated with high pressures, rendering them less feasible for widespread applications (Alejandro, 2019). Each design must factor in safety mechanisms, such as venting, to prevent dangerous pressure build-up. Given liquid hydrogen's energy density, its attractive scalability underscores the importance of understanding these design characteristics for their successful implementation of hydrogen storage technologies.

The longevity of liquid hydrogen tanks is critical and typical designs can last years with proper maintenance. However, challenges such as energy costs associated with liquefaction and the necessity for thermal insulation to prevent boil-off pose significant barriers to economic viability. Effective insulation can reduce boil-off rates, contributing to hydrogen loss. For instance, a well-designed 50 m^3 tank may exhibit a boil-off rate of approximately 0.4% per day, while larger tanks can achieve rates as low as 0.02%, illustrating the effectiveness of improved insulation technologies (Andersson & Grönkvist, 2019).

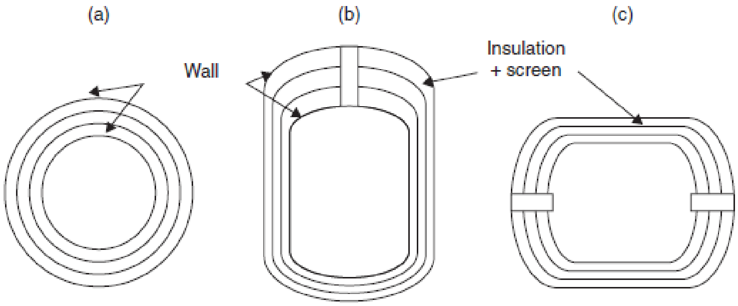


Figure 2.24: Different Shapes of Storage Tanks (Source: Basile, 2014)

Key of Tank Types:

a. Spherical

b. Cylindrical

c. Horizontal (Basile, 2014)

Cylindrical tanks represent the most common method for liquid hydrogen storage and are also utilised for other liquefied gases such as natural gas, nitrogen, liquid petroleum, and helium. Spherical tanks remain a possibility but require suitable support systems. In closed systems, pressure risks can escalate to dangerous levels, necessitating proper venting of the tanks.

Liquid hydrogen storage presents various challenging issues, including the energy needed for the liquefaction process and heat insulation for storage tanks to prevent boil-off effects. Different tank sizes exhibit varying boil-off rates. For example, a 50 m^3 tank has a boil-off rate of 0.4% per day, while a 100 m^3 tank exhibits a boil-off rate of 0.02% per day. A 20,000 m^3 tank also realises a 0.06% daily boil-off rate.

Boil-off leads to hydrogen loss; however, recent tank advancements minimise such occurrences. Common tank construction materials include Teflon, aluminum or its alloys, and steel. High storage capacities are achieved using aluminum. Cyro-compression, which utilises both cryogenic temperatures and high pressures, significantly mitigates boiling off. Nonetheless, the overall cost of these storage systems remains a barrier to their widespread adoption. The cost of storing hydrogen in liquid form comprises assembly, component purchases, certification, sensors, and calibration tests (Andersson & Grönkvist, 2019).

2.19.2. Compressed Hydrogen Storage

Compressed hydrogen storage is another common method, especially for transportation applications. Various tank designs have emerged to accommodate higher storage pressures while minimizing weight. Classifying compressed tanks into four types demonstrates the significant evolution of storage technology

(Basile, 2014). The increased utility of composite materials, particularly carbon fiber hybrids, addresses weight and pressure tolerance challenges but often at a higher cost.

Tensile strength is a critical parameter for compressed gas storage tanks. It defines the maximum pressure the tanks can safely withstand before failure. Enhanced material properties afford better performance and broaden the applications of compressed hydrogen, including vehicle fuel and other energy uses. Continued advancements in tank design and material science drive mass adoption of hydrogen technologies across various markets, aligning with broader goals of reducing carbon emissions and establishing a hydrogen economy.

Key barriers remain regarding cost and infrastructure. Producing lightweight yet robust tanks can be expensive, with carbon fiber comprising a substantial portion of total material expenses. As the hydrogen economy progresses, ongoing research and development efforts are needed to optimize manufacturing processes and reduce costs (Basile, 2014).

Compressed hydrogen (H_2) can also be stored. The storage units must tolerate higher storage pressures. The tanks are classified into the following four types:

- Metal tanks made from aluminum or steel.
- Metal tanks with filament windings made from aluminum and glass fiber, steel and carbon fiber, or steel and aramid.
- Composite material fiberglass with a metal liner, made from aluminum and glass or aluminum and aramid.
- Composite material fiber with a polymer liner, made from carbon and polyether.

These various types illustrate how tanks have evolved into lightweight containers capable of withstanding higher pressures. The development of efficient storage tanks paves the way for hydrogen applications across diverse sectors, including vehicle fueling, cooking, and heating.

The tensile strength of the material used is an important parameter to monitor when fabricating compressed gas storage tanks. This strength is defined as force per unit area—the maximum stress a material can withstand before it fractures when pulled, stretched, or pushed. For non-uniform materials, tensile strength is often defined simply as a force or as a force per unit width. Generally, tensile strength is measured in pascals (Pa) or megapascals (MPa).

Compressed hydrogen is the most practical form of hydrogen preferred by most car manufacturers; its efficient storage infrastructure has the potential to open new markets. These tanks provide superior technology, with no alternatives currently outperforming them in terms of both volumetric and gravimetric storage densities while also maintaining relative cost-effectiveness. Metal-lined composite and all-composite tanks have undergone numerous developments for utilization in the transportation sector, with extensive advancements in tank performance leading to extensive deployments as prototypes for gaseous hydrogen filling stations.

However, significant challenges remain in terms of costs. Hydrogen stored in this form requires pre-cooling and strict monitoring of the filling process for its intended applications. The cost of tanks continues to pose a barrier to large-scale hydrogen storage in compressed form. Carbon fiber remains relatively expensive, contributing approximately 75% of total material cost and about 50% of overall storage system cost. To mitigate the cost of compressed hydrogen storage systems, reducing the mass of carbon fiber is necessary (cite). The Department of Energy (DOE)-funded Quantum project in the United States, focusing on weight, thermal modeling, and cost aspects, has demonstrated significant advancements. Quantum reports their "full-scale" storage tank, with an inner volume of 160 L (approximately 6.3 kg H_2 at 700 bars), potentially meets the 1.5 kWh/kg target. Their 700-bar system has an average density of approximately 0.8 kWh/L. The Quantum tank is depicted in Figure 2.25. Meanwhile, Lincoln Composites' Tuffshell® tank has showcased commendable performance, achieving a gravimetric storage density of 1.61 kWh/kg at 700 bar (Type IV) hydrogen storage cylinders. However, numerous enhancements remain necessary for further cost reductions.

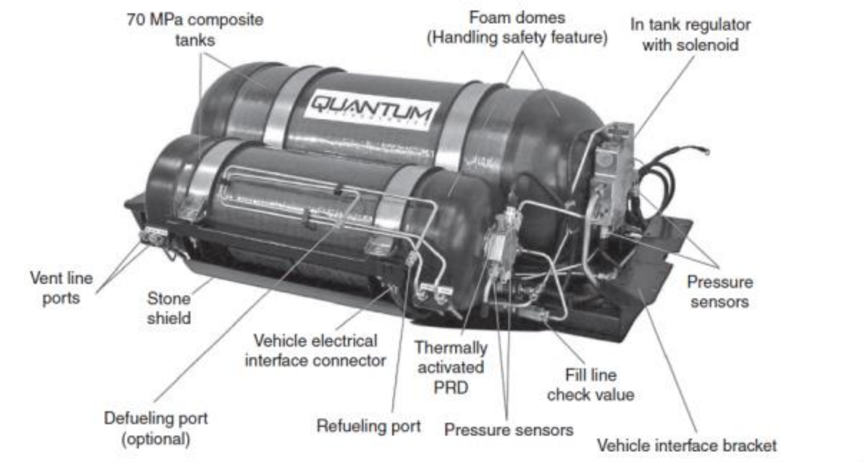


Figure 2.25: Quantum storage tank for compressed hydrogen (Basile, 2014)

Mass production of hydrogen-powered vehicles is feasible only with an established refueling infrastructure, which hinges on developing ideal storage tanks. Substantial improvements are still needed in compressed hydrogen storage tank technology to facilitate large-scale adoption. These improvements include the development of low-cost fibers utilised for fabricating storage tanks. Continuous safety studies are essential to reduce the risks associated with compressed hydrogen. Alternatives involving large-scale hydrogen storage using underground tanks have also been considered (Züttel, 2003). These consist of the same materials used for traditional tanks; however, concerns arise regarding corrosion given the distinct underground environment compared to air.

2.19.3. Physisorbed Hydrogen Storage

Physisorbed hydrogen storage involves non-dissociative physical interactions between gaseous hydrogen molecules and solid surfaces, primarily through van der Waals forces. This reversible process complements the exploration of innovative hydrogen storage methods; however, it currently faces limitations in practical capacity. Physisorption relies on interactions between hydrogen and solid surfaces, such as carbon nanofibers and carbon nanotubes. Materials like metal-organic frameworks (MOFs) show promising absorption capacities exceeding 8% by weight. Yet, the practical application of physisorption for large-scale hydrogen storage remains constrained by low volumetric densities (Eberle, Felderhoff, & Schüth, 2009).

The drive for research into materials capable of effective physisorption at room temperature while maintaining high hydrogen affinity propels innovation in this field. This study emphasizes the need for comprehensive hydrogen storage systems that optimize efficiency and practicality. Researchers are mainly focused on organometallic materials, as variations in pore size and shape altered by combining diverse organic structures with different metal centers can significantly influence hydrogen volumetric and surface area. The potential of carbon nanomaterials for physisorption is illustrated in Figure 2.26 below. Although developing ideal materials that function at room temperature is essential, reliance solely on physisorption for storage tanks cannot be justified; additional improvements are necessary (Eberle, Felderhoff, & Schüth, 2009).

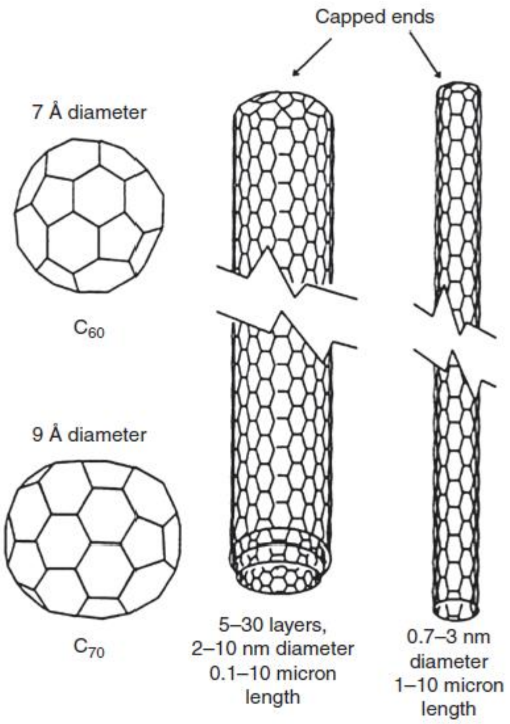


Figure 2.26: Carbon Nanomaterials for Physisorption (Basile, 2014)

2.19.3.1. Electrochemical Hydrogen Storage

Electrochemical hydrogen storage, mainly via nickel-metal hydride (NiMH) systems, presents an effective alternative for energy applications. The reversibility of hydrogen uptake in metal hydrides allows efficient energy storage and retrieval, emphasizing overall energy efficiency. NiMH cells, versatile across various portable and stationary applications, are ideal candidates for hydrogen integration within public transportation and energy storage (Zhou, Zhou & Sun, 2004). These electrochemical cells consist of an anode from hydride metal alloy and a cathode constructed from nickel hydroxide ($Ni(OH)_2$), with an electrolyte comprising an alkaline aqueous solution of potassium, sodium, and lithium hydroxides.

Typically, electrochemical cells have an average output voltage of around 1.2V and require low maintenance, although proper management is essential. This includes monitoring water levels to minimise heat exchanges during charging and maximising cell lifespan and capacity. NiMH cells can achieve volumetric energy densities of up to 140 Wh/L, making them suitable for high-capacity maintenance-free units. While current practical applications rely on single cells, research is underway to develop stacked cells to enhance voltage and power output (Zhou, Zhou & Sun, 2004).

2.19.3.2. Geological Hydrogen Storage

Utilizing naturally occurring geological storage sites offers substantial potential for large-scale, environmentally friendly hydrogen storage solutions. Natural formations such as salt domes and depleted oil fields can provide significant storage capacities while ensuring safety. Investigating these sites' chemical and physical properties is crucial to formulating strategies for safe, long-term hydrogen storage and addressing the challenges associated with hydrogen interactions within geological matrices. This method also represents a promising avenue for seasonal energy storage and underscores the potential for large-scale hydrogen solutions (Züttel, 2003). This approach is similar to the underground storage of radioactive waste; understanding chemical and mineral compositions and physical properties, such as permeability to liquids and gases, is vital. Ongoing research continues to explore the viability of using these natural cavities for hydrogen storage, although challenges related to their physical and chemical properties remain.

Understanding hydrogen storage mechanisms is critical to assessing hydrogen’s potential as a clean energy carrier. Identifying advantages and challenges across various storage methods lays the foundation for addressing research questions related to hydrogen's practical applications, economic viability, and sustainable energy transition. Insights derived from this section will provide a basis for future technological advancements and policy developments, contributing to the realization of a hydrogen economy.

2.19.4. Chemical Hydrogen Storage

Hydrogenated materials for storage have sparked substantial interest, evolving from simple metal hydrides to complex hydrides and nanomaterials. Hydrides constitute the most naturally occurring elements in the periodic table, with hydrogen interacting through metallic, ionic, and covalent bonding. Chemical hydrogen storage, also known as chemisorption, can offer considerable amounts of hydrogen gas per unit mass and volume, in contrast with physisorption, which demonstrates limited volumetric storage densities but faster adsorption and desorption cycles.

Despite certain limitations, such as the high energy requirements necessary to reverse chemical bonds or interactions, using materials that chemically bind hydrogen appears promising. Should these materials be able to bind hydrogen at higher volumetric densities than liquid hydrogen, they could facilitate large-scale storage opportunities. Ideal materials for chemisorption should provide high release rates, gravimetric and volumetric hydrogen storage capacities, and optimal storage reversibility at ambient or moderate temperature conditions (80–100 °C). Other essential attributes include high thermal conductivity, stability, affordability, longevity, and resistance to poisoning.

Enthalpy changes in hydrogen complex formations are critical as they influence both the rate and ease of conversion and relate to the enthalpy of the reverse reaction that liberates hydrogen. Monitoring these enthalpy changes assists in efficient heat management during operation. While some complexes have successfully reduced enthalpy during hydride formation, developing materials with both low enthalpies and high storage capacities remains a challenge. Metal hydride reactors usually operate at pressures lower than those of compressed hydrogen tanks, mitigating safety concerns associated with explosion risks.

Safety concerns mainly stem from the hazardous effects of the hydrogenated materials or pyrophoric characteristics. High costs remain a significant obstacle in the quest for efficient hydrogen storage solutions. In addition, hydride complex materials must be affordable and durable. The elements selected for the complexation reactions should prioritize availability, avoiding rare elements that are scarce or in high demand. For instance, although lithium is abundant, its demand in other industries inflates its price. Catalysts used in decomposing reactions may also pose a challenge if they contain rare earth elements. Metal hydrides are typically synthesized using metallurgical techniques; complex and chemical hydrides are developed through conventional chemical operation methods.

Numerous approaches for processing metal hydrides have evolved. Simple methods include heat treatment and cyclic hydriding/dehydriding. In contrast, more intricate methods have emerged, such as thin film deposition, sol-gel processing, and high-energy mechanical ball milling. A novel technique refers to scaffolding, which utilises nanoparticles to deposit storage materials into the nano-sized pores of host materials. The intended application also influences material choices. Various materials exhibit high storage capacities, including borohydrides, amide/imide complexes, nanomaterials, and metal hydrides.

Several designs for hydride reactors have been patented. They typically involve chemical hydrogen stored in metallic tanks divided into chambers. Hydride reactors are often placed within thermostatic baths to regulate temperature and minimize heat transfer issues. Stacking individual hydride reactors is one approach to enhancing storage capacity for large-scale applications. Some of the materials discussed in detail are based on findings from Basile (2014).

2.19.5. Metal Hydrides

Various metals can reversibly combine with hydrogen, rendering them suitable for hydrogen storage. Examples include pure metals, alloys, and intermetallic compounds. Titanium and zirconium are examples of pure metals utilised for this purpose, while alloys and intermetallics are more commonly employed. These materials can achieve high volumetric densities up to 115 kg/m^3 though they typically exhibit low gravimetric densities and high enthalpy changes during the formation of hydride complexes.

The processes associated with hydrogen uptake in metals are typically referred to as "sorption," while the process that releases hydrogen is known as "desorption." According to Dutta (2014), the sorption process can be succinctly divided into distinct steps, including the physisorption (desorption) of molecular hydrogen:

i. Hydrogen molecules adsorb weakly onto the metal surface.

$$Metal + H_2 \rightarrow Metal - H_2$$

ii. The hydrogen undergoes surface dissociative chemisorption, yielding surface hydrogen atoms.

$$2Metal - H_2 \leftrightarrow 2Metal - H_2$$

iii. Hydrogen is subsequently surface-absorbed, leading to sub-surface hydrogen atoms.

$$Had \leftrightarrow Hab$$

iv. Diffusion transports hydrogen from subsurface atoms to bulk regions.

The slowest step, known as the rate-determining step, governs the overall rate of hydrogen conversion into metal hydride. Determining the kinetics of relevant steps requires techniques such as gravimetric analysis or spectroscopy. Gravimetric storage density is a limiting factor for the industrial applications of metal hydrides and intermetallic compounds, notably in transportation. Magnesium hydrides offer better gravimetric density, rendering them more prevalent in market applications (Dutta, 2014).

2.19.6. Complex Hydrides

Transition metals, notable for their variable oxidation states, can form various hydrogen complexes yielding complex hydrides that typically provide high volumetric densities due to their transition metal hydrogen bonds. However, these complex compounds often require extreme temperatures (approximately 200°C) for thermal dissociation. Many of these dissociation reactions exhibit irreversible characteristics; for instance, Mg_2FeH_6 is an example of a metal complex.

2.19.7. Chemical Hydrides

Chemical hydrides, characterised by high gravimetric densities, include ammonia, methane, borohydrides, and boranes. However, the dehydriding process is challenging or impossible to reverse for many of these chemicals. Hydrogen desorption typically occurs through thermal decomposition at very high temperatures, presenting practical challenges for large-scale applications. Ongoing research seeks to address the destabilization of these chemical hydrides, facilitating hydrogen release at lower temperature conditions (Zhu et al., 2015).

2.19.8. Borohydrides and Boranes

Borohydrides contain BH_4 complexes, showcasing the highest theoretical gravimetric hydrogen densities among this category of compounds. While certain varieties possess high stability, others pose instability, complicating hydrogen storage efforts. Sodium borohydride ($NaBH_4$) is viewed as the most promising hydride; however, the hydrogen must be regenerated via hydrolysis, a process limited in practicality.

Consequently, alternative regeneration methods are crucial. This limitation curtails large-scale application potential, particularly within the transportation sector. Substitution reactions have enhanced their thermodynamic properties, enabling operational temperatures of approximately 200 °C while consistently delivering hydrogen storage capacity.

Other chemical hydride candidates for hydrogen storage include ammonia and boranes. The ammonium complex of borane (NH_4BH_4) can decompose at high temperatures to yield substantial hydrogen outputs via a four-step mechanism. The involvement of inert host structures can facilitate the decomposition process. Borazines remain excluded from these reactions due to their irreversible decomposition characteristics, rendering them impractical for large-scale hydrogen storage.

2.19.9. Alane and Alanates

Alane (AlH_4 complexes) forms another compound category, possessing a theoretical storage capacity reaching up to 10.1 wt% (Jeong, 2016). However, these alanes cannot undergo re-hydrogenation under onboard storage conditions and tend to be thermodynamically unstable in unmodified states. Conversely, they offer a high gravimetric storage capacity, are inexpensive, and are environmentally friendly, warranting further investigation. Alanates are another promising class of compounds akin to borohydrates.

Alkali metals can create intermediate ionic-covalent bonds with the AlH_4 complex. Research has revealed that by introducing small titanium quantities (approximately 2 wt%), the hydrating reaction of sodium alanate ($NaAlH_3$) can be rendered fully reversible. Ongoing investigations aim to develop more efficient catalysts based on titanium, zirconium, and iron to enhance the low-temperature kinetics of hydrogen release and improve the alanate absorption rate. Under standard conditions, alanate dissociation results in hydrogenated byproducts, with some unreleased hydrogen remaining. Higher temperatures are often necessary for complete hydrogen liberation, presenting a significant obstacle for practical uses.

2.19.10. Nitrides, Imides, and Amides

This group comprises compounds containing mono-, di-, or tri-substituted nitrogen ions and encompasses a significant range of properties applicable to various uses. Metal nitrides can store hydrogen via specific reactions as they can be hydrogenated via the following step:

$$Li_3N + 2H_2 \rightarrow Li_2NH + LiH + H_2$$

Such reactions typically occur at 255 °C, with efforts underway to lower the operational temperature through magnesium atom substitution. An imide is an organic functional group linked to two acyl groups. Hydrogen storage potential is feasible when unsaturated alkyl groups are applied, and amides show promising applications. Numerous organic compounds based on imides and amides, including purely organic amides, phosphorus amides, and sulfonamides, may serve as practical solutions for hydrogen storage.

2.19.11. Organic Hydrogenated Compounds

Certain cyclic organic compounds in liquid form offer potential as hydrogen storage media. These organic compounds could serve as liquid hydrogen carriers, being easily adaptable for use in hydrogen fueling stations. These hydrocarbons demonstrate gravimetric densities comparable to liquid hydrogen alongside higher volumetric densities. Notably, they can store hydrogen in liquid form under ambient conditions, which is an attractive feature. Examples under exploration include:

- ***Cyclohexane:*** storage capacity of approximately 7.2 wt%.
- ***Methylcyclohexane:*** storage capacity of about 6.2 wt%.
- ***Naphthalene:*** storage capacity of 7.3 wt%.
- ***Carbazoles:*** storage capacity of 6.2 wt%.

The dehydrogenation catalysts utilised are platinum nanoparticles supported on aluminum oxide. Conversely, carbazoles present significant disadvantages, such as high decomposition temperatures and melting points. Furthermore, water's action may decompose some metal hydrides, potentially as an alternative to energy-intensive thermal decomposition. The hydrogen-bearing hydrides can be safely stored and handled as liquids, facilitating more effortless transfer. A controlled quantity of water is systematically added to the oil slurry to yield hydrogen as necessary during the hydrolysis process, which is typically exothermic, thus negating additional energy requirements.

2.19.12. Adsorptive Hydrogen Storage

The adsorption of hydrogen onto nanomaterials has gained considerable attention. This method employs nanoporous materials characterised by pore diameters typically less than 100 nm, with most practical applications utilising nanoparticles measuring around 50 nm. These materials offer large surface areas and pore volumes, facilitating the adsorption of substantial hydrogen amounts at relatively low temperatures. In this storage method, hydrogen remains in its diatomic molecular form and can be compressed into high densities within the pores. Adsorption typically occurs on the material's surface, contrasting absorption, which takes place internally.

The predominant mechanism for hydrogen storage in these nanoparticles is physical; no chemical bonding occurs between hydrogen and the nanomaterial. This diverges from hydride formation, which requires chemical interaction whether ionic, covalent, or dative. A vital advantage of this method is the potential for high hydrogen storage density achievable at reasonably feasible and practical temperatures. Several nanomaterials under continued investigation are further discussed below.

2.19.13. Porous Solids

Certain solid materials exhibit high porosity, facilitating hydrogen particle adsorption. As previously noted, these interactions are physical rather than chemical, driven by processes such as van der Waals forces and electrostatic interactions between the gas and the solid surface. The gas that has been adsorbed is called the "sorbate," while the material performing the adsorption is termed the "adsorbent." Interaction types rely on the physical and chemical properties of both the gas and the adsorbent.

The symmetry of hydrogen atoms negates polarity, resulting in a non-dipole molecule. Consequently, hydrogen adsorption on solid surfaces primarily arises from van der Waals forces, with electrostatic interactions playing a minimal role. Regardless of the interaction type, adsorption within micropores is enhanced due to the overlapping potential energy fields formed on pore walls, referred to as adsorption potentials. This potential typically increases with decreasing pore widths or diameters. Proper evaluation of a material's potential performance for adsorptive hydrogen storage necessitates careful consideration of factors, including pore size, surface area, pore volume, and surface chemistry. The intricate interplay of these parameters requires further investigation to enhance their application on a large scale.

2.19.14. Porous Carbons

The adsorption of hydrogen onto carbon-based materials remains an ongoing area of study, with various material types proposed for hydrogen storage. Activated carbon, carbon molecular sieves, templated carbons, carbide-derived carbons, carbon xerogels, aerogels, cryogels, nanotubes, and nanofibers represent just a few options. These carbon-based materials are porous structures derived from solid organic precursors, with their properties influenced by both the raw materials utilised and the activation processes; they exhibit varying pore sizes from macropores to micropores.

Graphene sheets are a prime example, with inherent defects resulting from their production processes impacting adsorption capacity. The unique sieving properties of carbon molecular sieves (CMSs) stem from the narrow pore constrictions resulting from carbon deposition within porous substrates. Templated carbon can be synthesized using soft or hard templating methods, with soft templating emerging as a particularly innovative method. Activated carbon exhibits considerable promise for hydrogen storage, demonstrating capacities around 5.5 wt% at -196.1 °C, with 6.4 wt% reported at 2.0 MPa and -196.1 °C (Sevilla et al., 2011). Other reports indicate even higher values of up to 7.3 wt% at similar conditions (Zhang, 2012). As hydrogen uptake varies with temperature, these observations highlight the necessity of continued research into various carbon materials (Rockstroh et al., 2005).

2.19.15. Zeolites

Zeolites are crystalline porous aluminosilicates formed from SiO_4 and AlO_4 tetrahedra. Variants formed from other elements are termed zeotypes, including aluminophosphates, Gallo phosphates, silicoaluminophosphates, zincophosphates, and others. Research on zeolites for hydrogen storage is limited; their dense frameworks typically result in low pore volumes, thus restricting their application within the hydrogen storage sector.

2.19.16. Metal-Organic Frameworks (MOFs)

Metal-organic frameworks involve metal ions or clusters bonded by organic compounds in crystalline microporous materials (Hirscher and Panella, 2007). Compared to traditional materials like zeolites, MOFs offer larger surface areas, higher porosity, and flexible, customisable porous structures, making them ideal candidates for hydrogen storage (Garg et al., 2021). MOFs exhibit the highest specific surface areas, yielding maximum gravimetric hydrogen absorption at low temperatures (Balderas-Xicohtencatl, Schlichtenmayer, and Hirscher, 2017). The organised porosity of distinct types of MOFs facilitates effective gas trapping, including hydrogen (Garg et al., 2021).

2.19.17. Commercialisation of Hydrogen

The complexities of hydrogen commercialisation underscore the urgent need for infrastructure development and the related cost implications. Hydrogen commercialisation is essential for transitioning to a sustainable energy economy amid rising global energy demands and climate change mitigation. Industrial hydrogen production marks the beginning of the hydrogen life cycle, which is critical for its widespread use. While pure hydrogen (white hydrogen) exists naturally, it is scarce and must be extracted from various chemical compounds through diverse methods to effectively contribute to commercialisation (Assabumrungrat et al., 2020).

Hydrogen's production versatility enhances energy security and reduces dependence on specific raw materials, with sources like organic waste, ethanol, metallurgical slag, and biomass (Burton et al., 2021; Younous et al., 2018; Turner, 2004). This varied approach aligns with broader environmental goals (Costine & Loh, 2016).

Currently, hydrogen production mainly relies on fossil fuel raw materials and steam reforming, appropriate for the early stages of the hydrogen economy. A cyclical challenge exists, where low demand for hydrogen vehicles leads to inadequate infrastructure, which in turn stifles vehicle availability. Nonetheless, hydrogen is a promising renewable energy source aimed at mitigating greenhouse gas emissions (Hydrogen Production Processes, 2021).

Hydrogen production is categorized based on carbon footprints, with green hydrogen produced via renewable energy through water electrolysis, blue hydrogen generated from natural gas with CO_2 capture, yellow hydrogen from nuclear energy, and grey hydrogen from fossil fuels without emissions reduction (IRENA, 2020). The current cost of green hydrogen is approximately $10 per kg, making it less accessible than blue and yellow hydrogen, which are around $2 per kg. Large-scale production could reduce costs, but additional investments in distribution infrastructure are necessary. In 2019, global hydrogen consumption reached 75 million tons, primarily for oil refining and ammonia production, with over 75% sourced from natural gas, while about 0.1% came from electrolysis. Natural gas hydrogen costs are estimated between $1.5 and $3 per kilogram (Assabumrungrat et al., 2020).

The market cost of hydrogen varies with purity levels, currently between 95% and 98%, and production occurs at pressures of 1.0 to 4.2 MPa. Raw materials like natural gas are heated (350-400 °C) and undergo desulfurization, followed by cooling and several conversion stages to yield hydrogen (95% to 98.5% purity) (Assabumrungrat et al., 2020). For higher purity, the process includes an adsorption separation section, cooling the mixture to remove moisture, and achieving 99.99% purity at 1.5 to 2.0 MPa. Traditional methods may also utilize catalytic oxidation of water vapor over hot coal at about 1000 °C, costing $2–$2.5 per kilogram, potentially decreasing to $1.50 with shipping (Assabumrungrat et al., 2020).

Hydrogen can also be produced through the electrolysis of pure water or via thermochemical and biochemical methods using biomass. The thermochemical process requires heating biomass in the absence of oxygen (500 to 800 °C), projecting costs of $5 to $7 per kilogram, with future reductions anticipated to $1.0 to $3.0 (Assabumrungrat et al., 2020). Enzymes can generate hydrogen from polysaccharides at 30 °C and standard pressure, costing around $2 per kilogram. A 2006 study by the London Hydrogen Partnership indicated that daily production of 141 tons of hydrogen could power 13,750 buses, showcasing potential demand.

In 2007, Purdue University developed an aluminum alloy method for hydrogen production from water. Future hydrogen production using electricity from fourth-generation nuclear reactors is expected to match gasoline prices at approximately $3 per 3.8 liters (Assabumrungrat et al., 2020). A midsize car using 158 kg of aluminum could travel around 560 km, with future costs of $63 ($0.11/km).

Research from UC Berkeley in 1999 revealed that oxygen- and sulfur-deprived algae significantly increase hydrogen production (Hydrogen Production Processes, 2021). Green algae like Chlamydomonas reinhardtii can generate hydrogen from seawater or sewage, and household hydrogen production using natural gas or water electrolysis is feasible (Melis & Happe, 2001).

In 2007, ITM Power Plc launched a household electrolyser for hydrogen production (ITM Power PLC, 2007), which could produce hydrogen at 75 bar from water, powering a bi-fuel vehicle for up to 40 kilometers. This innovation, aimed for production in 2008, achieved a reduced cost of $164 per kW (Shi, Liao, & Yanfei, 2020).

By late 2006, over 800 stationary fuel cell power plants globally produced around 100 MW. In 2005, Melt Carbonate Fuel Cells (MCFC) led new installations, followed by Phosphate Technologies Fuel Cells (PAFC) and Proton Exchange Membrane Fuel Cells (PEMFC), especially in 10 kW setups. Hydrogen combustion is emerging as a viable alternative to natural gas for heating, with Northern Gas Networks planning to implement hydrogen in Leeds (Shi et al., n.d.).

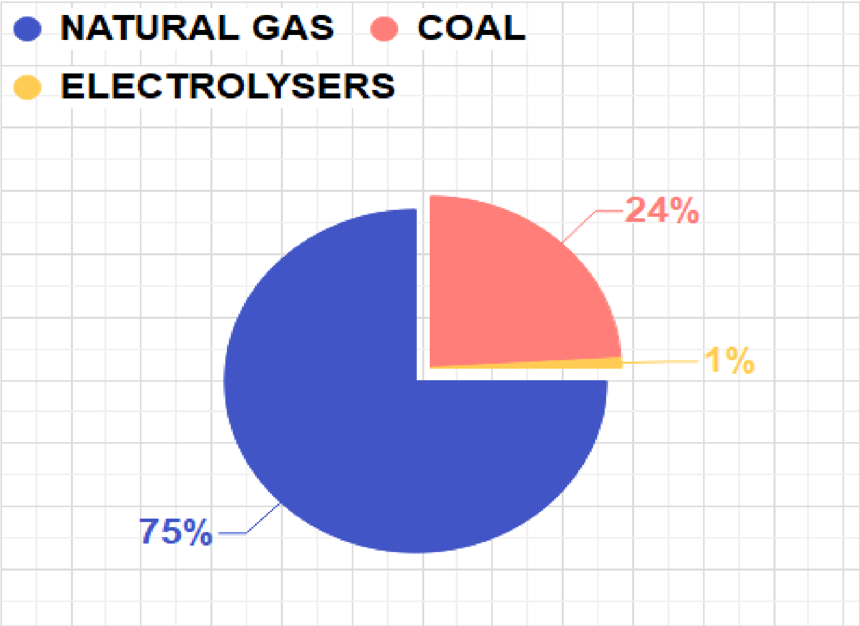


Figure 2.27: Level of Commercialization of Different Energy Sources Globally (**Source:** Author's Compilation, 2024).

Efforts to enhance efficiency have led to the combined use of fuel cells and gas turbines. Fuel Cell Energy has pioneered a hybrid model with SOFC fuel cells, achieving nearly 70% efficiency. The 2005 Energy Bill in the U.S. provided 30% investment tax credits for fuel cell installations from 2006 to 2008. Electricity generated by fuel cells in Japan and South Korea ranges from $0.015 to $0.02 per kWh (Mostafaeipour et al., 2019). Tables 2.5 and 2.6 summarise significant companies involved in hydrogen production and utilisation in the transportation sector.

Table 2.5: Major Hydrogen Producers for Heating Worldwide

Company Name	**Type of Plant**	**Plant Size**
Ansaldo Fuel Cell – Italy	MCFC	500 kW - 5 MW
FuelCell Energy – USA	MCFC	250 kW - 1 MW
GenCell – USA	MCFC	40-100 kW
Ishikawajima-Harima Heavy Industries – Japan	MCFC	300 kW - 1 MW
MTU CFC Solutions – Germany	MCFC	200 kW - 3 MW
Fuji Electric – Japan	PAFC	100 kW - 1 MW
Korea Gas – Korea	PAFC	40 kW
UTC Fuel Cells – USA	PAFC, MCFC, PEMFC	200 kW

Source: Author's Compilation (2024).

Table 2.6: Hydrogen Applications in the Transportation Sector

Company Name	**Type of Plant**	**Plant Size**
Ballard Power Systems – Canada	PEMFC	1-250 kW
General Motors USA	PEMFC	75-300 kW

Company Name	Type of Plant	Plant Size
Hydrogenics – Canada	PEMFC	7-65 kW
J-Power Japan	SOFC - fuel cells, gas turbines, and steam turbines	
Mitsubishi Materials Japan	SOFC	10 kW
Mitsubishi Heavy Industries Japan	SOFC, PEMFC	200 kW
Rolls-Royce Group plc – UK	SOFC	80 kW
Siemens AG Power Generation – Germany	SOFC	125 kW
Ztek – USA	SOFC	25 kW - 1 MW
Cummins Power Generation – USA	SOFC	3 kW
InEnergy Russia	SOFC, PEMFC	1-100 kW

Source: Author's Compilation (2024).

2.20. H_2 and Transport Sector: Economic Viability and Market Potential

Currently, steam reforming from fossil fuels remains the most economically favorable means of hydrogen production despite the associated greenhouse gas emissions. The simultaneous underperformance of hydrogen vehicle demand and the insufficient development of refueling infrastructure has created a cyclical dilemma. Nevertheless, significant potential exists for hydrogen as a renewable energy source, mainly if the necessary infrastructure can be effectively established (Hydrogen Production Processes, 2021).

The color coding of hydrogen production processes provides a clear assessment of the environmental impact of various hydrogen types. Besides the white hydrogen (pure hydrogen that occurs naturally), current common classifications include green hydrogen (produced from renewable resources via electrolysis). Green hydrogen is deemed the most environmentally friendly; blue hydrogen (derived from fossil fuels with carbon capture technologies), yellow hydrogen (produced using nuclear energy), and grey hydrogen (resulting from fossil fuel sources without emissions mitigation) (Costine & Loh, 2016; IRENA, 2020). Table 2.7 below illustrates the different hydrogen color codes on the market.

Table 2.7: Various hydrogen colour codes on the market

Carbon intensive	**Color**		**Fuel**	**Process**	**Products**
	Black hydrogen		Coal	Steam reforming	H_2 + $CO_{2(RELEASED)}$
	Brown hydrogen		Coal	Gasification	H_2 + $CO_{2(RELEASED)}$
	Grey hydrogen		Natural gas	Steam reforming	H_2 + $CO_{2(RELEASED)}$
	Turquoise hydrogen		Natural gas	Pyrolysis	H_2 + $C_{(SOLID)}$
	Blue hydrogen		Natural gas	Steam reforming	H_2 + CO_{2}(% CAPTURED AND STORED)
	Red hydrogen		Nuclear power	Catalytic splitting	H_2 + O_2
	Purple/Pink hydrogen		Nuclear power	Electrolysis	H_2 + O_2
	Yellow hydrogen		Solar power	Electrolysis	H_2 + O_2
	Green hydrogen		Renewable electricity	Electrolysis	H_2 + O_2
Low carbon	White hydrogen		N/A	Naturally occurring	H_2

Source: Auther's Compilation (Adapted from Hudson, 2022).

Since hydrogen is an energy vector (not a source) that can be produced, depending on the type of source or process used to produce hydrogen, the colour can be identified. For each type of hydrogen, a price can be defined according to the source and the efficiency of the technology used (Hudson, 2022). In many cases, the cost of producing hydrogen is linked to the cost of electricity, and the colour codes are further discussed below.

- ***Grey hydrogen:*** is extracted from fossil sources such as methane or coal, resulting in the massive production of CO2, which is then released into the environment without any other use. This is the most widely used method.

- ***Blue hydrogen***: It is produced from sources and processes that release CO_2 into the environment, but which is then captured and stored (and in some cases reused in other processes). In this case, we speak of Carbon Capture and Storage (CCS).
- ***Green hydrogen:*** This is produced by water electrolysis, using only electricity from renewable energies. The electrolysis process can split water into hydrogen and oxygen molecules using electric energy. Since production is based on renewable energy, hydrogen is produced without CO_2 emissions.
- ***Pink hydrogen****:* It is extracted by electrolysis through electric current produced by nuclear power plants. Nuclear energy is only available in certain countries, such as France. Italy has been without proprietary nuclear power for many years, and even Germany, which has its nuclear power plants, is decommissioning them. It is, therefore, a type of hydrogen that has a well-defined geographical location. On the other hand, the price of nuclear energy is low (about €50 per MWh, remunerating the investment of the plant which could otherwise drop to €33 per MWh).
- ***Turquoise hydrogen****:* It is achieved through pyrolysis, sometimes using catalysts or membranes, which in high temperature reactors (800-900°C) splits carbon and hydrogen from the natural gas molecule or other sources. This process leads to hydrogen gas and carbon dust without emitting CO_2 into the atmosphere. It is also an energy intensive process due to the high-temperature requirements and has yet to be efficiently industrialised. However, it has the potential to become a conversion system that can easily be adapted to all the processes that use natural gas today.
- ***Gold hydrogen****:* Gold hydrogen is another term sometimes used to describe naturally occurring hydrogen, as well as hydrogen produced by fermenting microbes found in depleted oil wells. It not only offers another low-cost pathway for hydrogen, but also extends the life of oil fields rather than leaving them as stranded assets. The production and extraction process for gold hydrogen does, however, rely on CO_2 capture for carbon neutrality.
- ***Black and brown hydrogen****:* Black and brown hydrogen represent the traditional process for making hydrogen, which uses either black or brown coal (lignite). The method releases high amounts of CO_2 and carbon monoxide into the atmosphere. In 2020, around a fifth of hydrogen was still made using coal, according to the International Energy Agency (IEA).
- ***Yellow hydrogen****:* Yellow hydrogen typically refers to hydrogen made using electrolysis powered by solar energy. However, it is sometimes also used to describe electrolysed hydrogen created from a mix of renewables and fossil fuel power.
- ***White hydrogen****:* White hydrogen is naturally occurring hydrogen found in underground deposits. In recent years, scientists have found that more deposits exist than previously thought. These can often be accessed relatively easily by drilling a well. One well in Mali has been actively delivering

hydrogen since 2012. Exploratory projects are underway in Brazil, Australia and other parts of the world. Science Business, a network of universities, companies, and research and policy organizations estimates that natural hydrogen may be even cheaper to produce than gray hydrogen, at under $1/kg. While white hydrogen is a carbon-free fuel, the environmental impact of the extraction methods must be considered.

Notably, the production costs of green hydrogen currently hover around $10 per kg, significantly more expensive than the $1.50 to $3 per kg associated with hydrogen produced from natural gas. To stimulate market growth, centralised hydrogen production facilities could help reduce overall costs, provided the distribution infrastructure is concurrently developed (Costine & Loh, 2016; IRENA, 2020).

2.21. Distribution Challenges and Infrastructure Development

The effective distribution of hydrogen remains a significant challenge impacting its commercialization, necessitating an understanding of its unique physical properties. Hydrogen is the smallest and lightest of all gases, granting it a high energy content by weight and presenting obstacles such as storage and containment leakage (Belliard, 2021). Its flammability, combined with a propensity to permeate materials, means that specialised handling infrastructure is essential.

Hydrogen can be distributed through several methods, including pipelines, high-pressure tube trailers, and liquid hydrogen tankers. Each method poses distinct technical challenges and costs. Pipelines are the most cost-effective means for large-scale transport, and hydrogen pipelines can operate at pressures typically lower than those used for natural gas systems, enhancing overall safety and efficiency (Parfomak, 2021). However, the initial infrastructure costs are high, and the materials used must be specifically designed to prevent hydrogen embrittlement.

On the other hand, truck transport using liquid hydrogen tankers or tube trailers provides flexibility, enabling hydrogen distribution to remote areas and serving as a backup during peak demand. For instance, tanker trucks can carry significant loads of liquid hydrogen, notwithstanding the high costs associated with its liquefaction (Demir & Dincer, 2018).

An increasingly viable alternative entails on-site hydrogen generation through electrolysis at fueling stations. This approach mitigates distribution challenges and costs by enabling localized production. The development of household or smaller-scale electrolysers reflects this trend, allowing consumers to produce hydrogen efficiently at points of use (Bellini, 2022). This localised model has the potential to significantly reduce the need for extensive distribution networks and enhance overall hydrogen accessibility.

2.22. The Role of Government and Policy

Successful commercialisation of hydrogen also requires supportive government policies and investment. Many advanced economies are introducing incentives to stimulate research, development, and deployment of hydrogen technologies. For example, Japan and the European Union aim for carbon neutrality by 2050 and see hydrogen as a crucial component of this transition (International Energy Agency, 2022). In contrast, emerging economies like Zimbabwe may face significant challenges given the current reliance on fossil fuels and the substantial investments needed for clean energy infrastructure.

While transitioning to a hydrogen-based economy is promising for reducing global greenhouse gas emissions, countries such as Zimbabwe must navigate their energy resource challenges and market contexts. Additionally, the global landscape remains complex due to competing interests and the potential for regressing into traditional energy sources, which may delay the implementation of "Net Zero" technologies (International Energy Agency, 2022). Net zero is the reduction of water, energy, and waste footprints that can improve the environment, save money, and help communities become more sustainable and resilient (US Environmental Protection Agency, n.d).

In conclusion, this section synthesizes the critical elements involved in the commercialisation of hydrogen. By comprehensively addressing production, distribution, and the crucial role of government policies in shaping the hydrogen landscape, this analysis is a solid foundation for understanding hydrogen's potential in both global and localised contexts.

By the end of 2008, 2,000 hydrogen car filling stations were in operation globally. Only 8% of the total built between 2004 and 2005 utilised liquid hydrogen; the remainder relied on petroleum gas. In January 2006, Mazda began selling the Mazda RX-8 bi-fuel car with a rotary engine capable of running on gasoline and hydrogen. By July 2006, the Berlin-based transportation company BVG (Berliner Verkehrsbetriebe) announced its acquisition of 250 MAN hydrogen-powered buses, aiming for operationalization by 2009, which would account for 20% of the fleet (Jokar et al., 2018; HTAC, 2009).

In 2006, Ford Motor Company started producing buses with internal combustion engines running on hydrogen. Prominent hydrogen production and use players included British BP, Mercedes Benz, Itawa International, and BOC Group (Ishaq & Dincer, 2021). Automotive applications predominantly leverage PEM cell technologies. In 2005, only one vehicle equipped with a PAFC fuel cell was manufactured; the remaining vehicles utilised PEM technology. Manufacturers successfully reduced hydrogen fuel cells' costs for cars from $275 per kWh in 2002 to $110 per kWh in 2005.

The US Department of Energy aimed to further reduce this cost to $30 per kWh by 2020 ("Hydrogen Production Processes", 2021). Nevertheless, companies like Ford and Renault have announced they will no longer pursue fuel cells for automobiles (Ishaq & Dincer, 2021), with General Motors also scaling back investments in this field. Thus, large corporations are now more focused on improving electric vehicles, including those with integrated fuel cells (IAEA, 2018). Forecasts projecting high and low hydrogen penetration scenarios in future markets, presented in Table 2.7, illustrate these dynamics.

Table 2.7: Forecast Scenarios of Hydrogen Adoption Penetration

Years	**2020**	**2030**	**2040**	**2050**
High Penetration	3.3%	23.7%	54.4%	74.5%
Low Penetration	0.7%	7.6%	22.6%	40.0%

(**Source:** IAEA, 2018).

Boeing forecasts that fuel cells will gradually replace auxiliary power units in aircraft, enabling them to generate electricity while the planes are on the ground and providing uninterrupted power during flight. The gradual implementation of fuel cells on new-generation Boeing 7E7s commenced in 2008 (IAEA, 2018).

These applications require substantial power within the railway transport sector, where the size of the power plant is less critical. The Japanese Railway Research Institute of Technology aimed to introduce hydrogen fuel cell trains by 2010, expecting trains capable of attaining 120 km/h speeds with ranges of 300-400 km without refueling. The prototype underwent testing in February 2005, while a hydrogen fuel cell locomotive with a capacity of 2,000 liters commenced operation in the United States in 2009 ("Hydrogen Production Processes", 2021).

In 2018, the Coradia iLint hydrogen fuel cell passenger train entered operation in Germany and Russia, while plans to prototype hydrogen-powered railway transport in Russia are underway. The Russian Ministry of Energy has been preparing a consolidated proposal to test an integrated implementation strategy for hydrogen energy technologies until mid-2021, focusing on the Sakhalin hydrogen project.

The low conversion cost of natural gas, estimated at $1.5-$3 per kg, remains a potent argument in favor of using natural gas for hydrogen production. In contrast, this cost rises sharply by 2.5 to 3 times when utilising the more expensive water electrolysis technology. Hydrogen fuel's profitability compared to traditional fuels proves crucial for TMH technologists. Current hydrogen train models more than double lifecycle costs, yet natural gas-based technology can potentially bring hydrogen costs down significantly (Hydrogen Production Processes, 2021).

In Germany, submarines such as the U-212 utilize hydrogen from Siemens AG's fuel production elements. Presently in service with the German Navy, the U-212 has received orders from Greece, Italy, Korea, and Israel. Hydrogen powers the submarine underwater, allowing for near-silent operation. In 2006, SOFC deliveries of submarine fuel cells commenced in the United States, while Fuel Cell Energy also pursued fuel cells with a capacity of 625 kW for military ships. Mitsubishi Heavy Industries conducted testing on its Urashima boat fuel cell PEMFC in August 2003.

In 2006, warehouse trucks constituted just under half of all new vehicle fuel cell installations. The expectation that replacing storage batteries with fuel cells would significantly reduce battery storage area usage led Walmart to complete its second test of fuel-cell-powered warehouse trucks in January 2007 ("Hydrogen Production Processes", 2021).

In mobile device electricity production, including mobile phones and laptops, approximately 3,000 devices were produced globally in 2006, consistent with 2005 figures, rising to 9,000 in 2008. The US Army is a significant consumer seeking lightweight, capacious, and quiet energy sources. The United States ranked first in portable application developments due to military demand, as Japan accounted for only 13% of all new developments in 2005. Prominent electronics manufacturers in this space include Casio, Fujitsu, Hitachi, NEC, Sanyo, and Toshiba. In the spring of 2007, Medis Technologies began marketing hydrogen fuel cells for mobile devices.

2.23. Hydrogen Politics

The EU's primary goal of decarbonizing the economy and gas industry creates opportunities for renewed interactions between Russia and the EU, extending beyond traditional Russian gas supplies. Such interaction could facilitate cooperation among states and development partners on producing and utilizing pure hydrogen from Russian natural gas without CO_2 emissions. The European Commission highlights that achieving carbon neutrality by 2050 is a critical priority, mobilizing all available resources ("Hydrogen Production Processes," 2021). In comparison, China lags behind a roadmap targeting neutrality by 2060 (Li, Phoumin, and Kimura, 2021).

Referring to the EU's approach as "climate-neutral" would be more accurate, as the initiative aims to reset CO_2 emissions affecting climate change. Employing mischaracterisations can lead to conceptual confusion, undermining the establishment of clear goals; thus, the EU has allocated over €1 trillion for these initiatives. The European Commission's new "Green Deal" emphasises utilising renewable energy sources (RES) and decarbonised gases, primarily hydrogen. Concurrently, hydrogen is recognised as both an energy carrier and a means to store excess electricity generated during periods of high renewable production.

Post-pandemic recovery and growth within the EU are expected to be anchored in a low-carbon energy model that is even greener than previously planned. This may lower the traditional demand for Russian gas while creating new avenues for its utilisation, particularly as a feedstock for hydrogen production if it is generated cleanly. Since approximately 80% of greenhouse gas emissions in the Russia-EU cross-border gas supply chain occur on the consumer side, it is most logical to initiate gas decarbonization at locations where hydrogen usage will continue. While investments in hydrogen production may be made to mitigate the energy crisis exacerbated by the Russia-Ukraine war, the long-term viability of such investments in Zimbabwe, where the nation may have to prioritize its own needs, remains uncertain. Furthermore, a regression to coal use in the Global North could further delay deploying "Net Zero" cleaner energy technologies (International Energy Agency, 2022).

2.23.1. Hydrogen Distribution

Understanding hydrogen's properties is essential for planning its distribution effectively. Hydrogen, the smallest and most abundant element, also stands as the lightest gas, possessing the highest energy content of any fuel by weight. Unlike methane and many other transported gases, hydrogen's low weight renders it highly susceptible to containment issues and permeation through materials. Hydrogen becomes extremely flammable and easily ignitable when mixed with air, owing to its wide combustibility range. Moreover, hydrogen's flame is nearly invisible upon ignition and cannot be mixed with odorants like LPG for easy detection, necessitating specialized detectors for leak identification (Belliard, 2021).

Specific metals and other materials may undergo embrittlement due to hydrogen exposure, rapid deterioration, and cracking. This necessitates heightened compression compared to traditional gases for increased energy density. At atmospheric pressure, hydrogen reverts to its gaseous state above -253 °C, requiring it to be supercooled to that temperature for efficient transport. Transporting hydrogen incurs increased costs due to lower energy density per unit volume relative to other fuels. Solid-state hydrogen carriers include pure liquids, solutions, and slurries (Dodds & Demoullin, 2013).

As indicated in Figure 2.28, hydrogen, much like ethanol, can be transported via pipeline, rail, ship, or truck. However, hydrogen is a gas at standard temperatures, leading to significant technological differences in transportation compared to other gases (Gielen & Simbolotti, 2005). Rail and truck transportation can efficiently address the distribution of hydrogen in compressed or liquefied forms. At the same time, it is generally cheaper to transport small gas quantities, this comes at the cost of lower energy density (Wakeley et al., 2008).

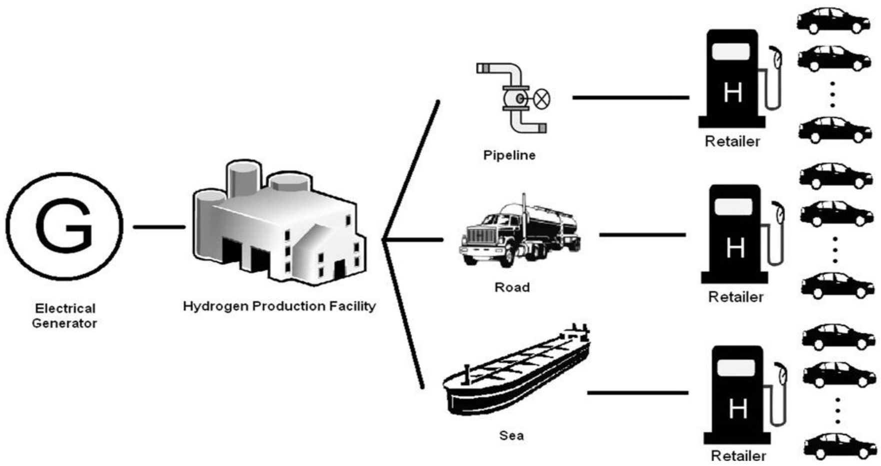


Figure 2.28: Hydrogen Gas Distribution Mechanisms (Mazloomi & Gomes, 2012:3030)

Like other commodities, hydrogen distribution depends on package types, transport distances, and delivery quantities. However, hydrogen's unique properties create significant challenges for transportation and storage. The transport and storage of hydrogen entail distinct technical and safety considerations. Distribution channels for hydrogen encompass pipelines, high-pressure tube trailers, and liquefied hydrogen tankers. Initial costs associated with establishing a new hydrogen pipeline network can be steep, while hydrogen's properties present unique challenges for pipeline materials and compressor design. Hydrogen's local or regional production could optimize resource use and mitigate distribution hurdles (Mintz et al., 2006).

Weighing centralised versus distributed production approaches necessitates careful consideration of trade-offs. While hydrogen production in extensive facilities remains inexpensive, distribution costs can offset these advantages. Conversely, generating hydrogen at point-of-use locations—such as fueling stations can reduce distribution expenses, though initial production costs would rise due to on-site infrastructure development. Systems such as Household Electrolysers link electrolysers to tap water and hydrogen storage tanks, incorporating fuel cells or Wankel engines for energy generation (Bellini, 2022). These systems can produce hydrogen at rates between 0.2 and 20 Nm^3/h, with capacities from 1 kW to 100 kW. Yet, significant limitations, including energy density at room temperature (roughly 30% of methane at 15 °C, 1 bar) and permeation through metal-based materials, persist. Most hydrogen consumed in the United States is generated on-site or close to large industrial sites (Mintz et al., 2006).

The final application of hydrogen may dictate its transportation method, as hydrogen could be utilised locally to produce end products (such as chemicals, fertilizers, or steel) or alternative fuels (like ammonia or synthetic fuels) that can be transported at lower costs. In some instances, pure hydrogen will be the desired product for transportation or high-temperature heating. The total transportation cost, considering conversion/reconversion, storage, and transportation, ultimately determines whether pure hydrogen is shipped (as gas or in a liquefied state) or via hydrogen carriers (like ammonia or liquid organic hydrogen carriers [LOHC]). Typically, pipelines and tube trailers deliver hydrogen as a gas, while cryogenic tanks are utilised for liquid hydrogen transport.

2.23.2. Hydrogen Distribution Using Pipelines

The first hydrogen pipeline system was commissioned in the Rhine-Ruhr metropolitan area (Germany) in 1938 and remains operational today. Over 5,000 km of hydrogen pipelines currently exist, with more than 90% situated in Europe, collectively covering above 1,500 km. By December 2020, the United States had 2,588 km of active hydrogen pipelines, primarily concentrated along the Gulf Coast in Texas, Louisiana, and Alabama, serving refineries and ammonia plants (Parfomak, 2021).

Transporting hydrogen as a gaseous fuel allows for lower cost distribution to individual consumers compared to electricity, while hydrogen's storable nature is an added benefit (Winsche, Hoffman & Salzano, 1973). The majority of pipelines function within closed systems managed by large merchant hydrogen producers and are situated near industrial consumers, such as petroleum refineries and chemical plants. Pipelines also transport liquid hydrogen from processing facilities to fueling stations, utilising pipelines to move liquid carriers ranging from pure liquids and slurries to solutions through either two-pipe or single-pipe systems (Moreno-Benito, Agnolucci, & Papageorgiou, 2017).

Hydrogen pipelines are known for their strong safety records, having traditionally operated at pressures below 1,000 pounds per square inch (psi). Hydrogen delivery pipes tend to be smaller in diameter with fewer interconnections to prevent leakage. Transporting hydrogen via pipelines requires specialised positive displacement compressors, making hydrogen gas piping relatively short since transporting feedstock (like natural gas or water) is typically more economically favorable than transporting hydrogen itself (Moreno-Benito, Agnolucci, & Papageorgiou, 2017).

Due to their high capacity and economies of scale, pipelines have emerged as the most cost-effective transportation method for gaseous and liquid commodities, including hydrogen, over long distances and in substantial quantities (Parfomak, 2021).

Liquid hydrogen distribution networks have proven expensive and complex to manage. Transporting liquid hydrogen (and slush hydrogen) poses numerous difficulties: both forms exist only at very low temperatures and evaporate rapidly due to the low latent heat of evaporation. As such, the transportation of liquid or slush hydrogen via pipeline is virtually non-existent (Takahashi, 2009). The current hydrogen pipelines in the United States primarily serve to transport hydrogen as feedstock to nearby refineries and ammonia facilities (Parfomak, 2021).

In fueling stations, hydrogen is delivered through low-pressure pipeline systems (300 to 1,000 psi). This approach is the most cost-effective method for transporting significant hydrogen quantities, although capacity remains limited; U.S. hydrogen pipelines currently serve less than 1% of the potential customer base. Ordinarily, hydrogen transportation pipelines range from 25-30 cm in diameter and operate at pressures of 10-20 bar. While steel pipes have become the standard, fiber-reinforced polymer pipes may offer a path toward reduced costs and improved performance. Pipelines can efficiently deliver hydrogen to numerous high-capacity users. However, significant energy is required to compress and pump hydrogen. Additionally, it is feasible to blend up to 20% hydrogen with natural gas in existing pipelines without substantial modifications (Parfomak, 2021).

2.23.3. Hydrogen Distribution Using Road Transport

Hydrogen can also be transported using trucks, trains, and ships. Although other distribution methods exist, road transport is crucial due to its ability to reach remote areas and provide backup supplies at fueling stations during peak demand. Trucks are likely to be the primary mode of transportation for alternative hydrogen carriers; this can occur through two primary methods: liquid truck transport and solid-state truck transport.

2.23.4. Distribution Using Tankers

Tanker trucks are commonly employed to transport liquid hydrogen over longer distances, especially in areas devoid of pipelines. These trucks can carry a maximum of 4,000 kg, double the payload transportable through gas tube trailers (Demir & Dincer, 2018). Liquid hydrogen is transported in insulated tanker trucks designed to maintain its low temperatures. While liquefaction incurs significant costs, this enables more efficient transport over longer distances (compared to high-pressure tube trailers). For mid-sized loads traveling long distances, liquid tankers are typically preferred, while pipelines are used for large loads over extensive distances. The limits on truck capacity are affected by the overall weight restrictions rather than volume, marking the alternative hydrogen carrier as a reusable material rather than a consumable fuel (Abdin et al., 2021).

2.23.5. Distribution Using High-Pressure Tube Trailers

High-pressure tube trailers usually hold around 300 kg of gas at up to 200 bar pressures. These trailers are principally employed for small deliveries to nearby customers, minimising the costs of transporting minor amounts of product. Tube trailers provide distinct advantages, including delivering hydrogen to customers not yet linked to a distribution pipeline. Compressed or liquid carriers can be transported by truck, railcar, ship, or barge using high-pressure tube trailers.

High-pressure tubes are ordinarily left at fueling stations or with customers to facilitate the delivery of compressed hydrogen. In some cases, the gas can be delivered by exchanging an empty trailer for a filled one (Chen, 2010). In contrast, the liquid carrier delivery method typically involves transporting pure liquids, solutions, or slurries between processing plants and fueling stations. Switching trailers is not common; liquid hydrogen is usually offloaded into dedicated storage tanks at refueling stations. Pure liquids are far easier to transport than solutions or slurries due to concerns about separation. Hydrogen's storage density can be enhanced by cooling and liquefying it.

Long-distance hydrogen transport typically employs cryogenic barges, tanker trucks, and railcars to deliver liquid hydrogen. The energy losses associated with liquefying hydrogen and the associated storage losses resulting from boil-off pose significant obstacles to adopting this transport method broadly. Gaseous hydrogen is mainly transported by tube trailers or pipelines, while liquefied hydrogen is conveyed via road tankers. For shorter distances and lesser amounts, gaseous hydrogen is mainly transported through tube trailers, which can be costly and are primarily utilised for journeys up to 320 kilometers (Chen, 2010; Parfomak, 2021).

Solid carriers entail handling limitations that necessitate alternative transportation methods. Solid-state materials can be offloaded and stored, with numerous practical challenges attached. Solid materials must remain on the delivery trailer for extended periods. Discharge of hydrogen from many solid-state carriers typically requires heat transfer. Endothermic desorption processes may be required for activated carbon or metal hydride-based materials. Consequently, the integration of heat exchange elements into delivery trailers becomes essential, leading to inflated costs (Chen, 2010).

The heat source or sink generally exists off vehicle trailers at the fueling station or reprocessing facility. In situ, charging and discharging of carrier materials necessitate trailer-based heat transfer systems and an off-board heat source or sink. Numerous delivery options can be employed utilising solid-state carriers. The most commonly used methods are the Trailer Drop-Off and Hydrogen Off-Load approach. The trailer can be deposited at a fueling station with hydrogen desorbing during peak demand or rapidly discharged into low-pressure storage tanks upon delivery. Compared to liquid carriers, solid-state options offer a broader range of delivery solutions. This delivery system resembles tube trailers, requiring each fueling station to maintain an on-site trailer to meet demand, with the trailer also functioning as storage (Chen, 2010).

2.23.6. Other Hydrogen Distribution Methods

Multiple methods exist for hydrogen distribution, including vehicle fueling, alternative carrier fueling, on-site hydrogen generation, and hydrogen fueling stations. In vehicle fueling arrangements, hydrogen typically exists in compressed and charged alternative carrier forms. Compressed hydrogen fueling entails delivering hydrogen to fill onboard tanks at pressures of 5,000 psi, requiring 6,250 psi of cascade storage at fueling stations.

This arrangement releases hydrogen from alternative carriers at the fueling station. When utilising an alternative carrier fueling method, hydrogen is not released from the airline at the station; instead, the carrier is delivered directly to the vehicle, where it discharges hydrogen while in operation. This method demands additional infrastructure for the onboard discharge equipment and advanced dispensers capable of removing discharged carriers at the fueling station (Chen, 2010).

By delivering the alternative carrier directly to the vehicle, the necessity for on-site discharge equipment and compressed hydrogen hardware at fueling stations is alleviated, potentially leading to significant capital cost reductions. However, the increased complexities of storing and discharging the carrier onboard the vehicle may negate some of these savings. Hydrogen can be delivered using hydrogen-rich compounds like ethanol, methanol, gasoline, and ammonia. These carriers present lower transportation costs, as they liquefy at room temperature and are typically easier to handle. Nevertheless, this approach may require additional conversion infrastructure, with the costs needing to be balanced against savings from transporting low-pressure liquids. Specific choices for hydrogen carriers, such as methanol and ammonia, further entail safety challenges and handling issues (Chen, 2010).

An additional method for hydrogen supply involves on-site electrolysis at fueling stations. The energy expended to produce and compress hydrogen in this scheme can be compared with the high heating value (HHV) of delivered hydrogen to local customers. Ultimately, hydrogen fueling stations are vital components within the hydrogen delivery infrastructure (Chen, 2010).

Table 2.8: Comparison of Hydrogen Distribution Channels

	Tube Trailer	**Pipeline**	**Liquid via Road**	**Liquid via Ships**
Suitability	Short-distance gas transfer	Short, medium, and large distance transfer of large and very large quantities in a gas state	Short and medium-distance transfer of large volumes of fuel	Very large quantities of gas for international transportation

	Tube Trailer	Pipeline	Liquid via Road	Liquid via Ships
Investment Costs	Around $300,000 per truck; plus $200,000–$1,000,000 per 100 km (depending on terrain)	Up to $400,000 per truck; $100 km (depending on terrain)	$1,550,000 for gas; up to $7,000,000 for liquid barges	
Operating and Maintenance Costs	Driver labor at around $18/hour	Approximately $0.03/kg for pipeline compressors	Driver labor at around $18/hour	Costs for crew labor and fuel consumption (unspecified)
Capacity	Up to 400 kg per truck	Up to 100 tons/hour	Up to 4,000 kg per truck	Up to 10,000 tons per shipment
Efficiency	94% per 100 km	Over 99% per 100 km	Vehicle fuel and liquefaction energy consumption	Unknown fuel use with 0.3% boil-off
Energy Consumption	Vehicle fuel consumption	Electricity requirements for pipeline compressors	Transport fuel	Transport fuel

	Tube Trailer	Pipeline	Liquid via Road	Liquid via Ships
Advantages	Small-scale deployment possibilities	Large and very large quantities can be transported to any distance with high efficiency and minimal varying costs; offers storage and buffering capabilities	Larger volumes than gas transportation	International transportation of massive quantities over long distances
Disadvantages	Limited small-scale delivery per vehicle; energy inefficiency; short-distance transport	Relatively high initial investment costs, requiring significant hydrogen flow to justify	Costs related to liquefaction and boil-off losses	Lack of experience for liquid hydrogen transfer; cost-effective only with large production and demand

2.24. Path Forward

A well-structured roadmap is needed to transition towards a hydrogen economy, particularly in Zimbabwe. This section emphasises identifying solutions for the barriers faced in producing, distributing, and adopting hydrogen technologies.

2.25. Chapter Summary

This chapter provided a detailed overview of the hydrogen energy sector, focusing on production, commercialisation, and distribution within the context of global energy trends. Emphasis was placed on the necessity for ongoing research and policy support to facilitate hydrogen adoption as an energy solution, especially in developing economies like Zimbabwe. This Chapter is important in this study as it technically, commercially and socially orients the reader on the hydrogen technologies and trends, which lays the base for developing the methodology and other following chapters. In conclusion, hydrogen holds substantial potential as an accessible, innovative energy solution for sustainable development in Africa, guided by strategic investments, research, and supportive policies. Chapter Three delves into the research methods and theoretical frameworks guiding the subsequent study. Thus, it enables meeting expectations while grounding discussions in the current literature and addressing how these factors relate to the study.

CHAPTER THREE

3.1. RESEARCH METHODOLOGY

Chapter Three outlines the research methodology employed in this study, articulating the electrolyser design foundations and methodological strategies adopted to explore hydrogen's role as a potential cleaner energy solution in Zimbabwe. This chapter begins by framing the philosophical approach, specifically the pragmatism worldview, which facilitates a mixed-methods design integrating both qualitative and quantitative techniques. This methodological choice is pivotal for understanding the complexities of energy innovation in an African context, where practical solutions must address real-world problems such as energy poverty and environmental sustainability. The research design encompasses various data collection methods, including literature reviews, surveys, and key informant interviews, used to gather insights from community members and organisational representatives of organisations involved in hydrogen technology. Subsequently, this chapter details the case study analysis and experimental design related to the electrolyser, along with sampling strategies and data analysis techniques employed in the study. In terms of electrolyser market global scanning, a comparative analysis was based on a defined criterion: manufacturer, technological specialisation, geographic presence, operational capacity, and cost of the prevalent technologies, as well as various manufacturers' strategies and innovations. Manufacturer evaluation was also based on their market presence, production capabilities, and strategic partnerships which influence their competitive dynamics in various regions such as North America, Europe, and Asia. A comprehensive discussion of the ethical considerations and safety protocols implemented throughout the research process is also provided. Thus, adherence to ethical standards was prioritised for the safety of participants. Finally, the chapter concludes by summarising the limitations encountered and the relevance of the discoveries that emerged during the electrolyser designing process, setting the stage for methodological application within the broader context of sustainable energy initiatives in Zimbabwe.

3.2. Introduction

Philosophically, the study is rooted in the pragmatic worldview approach (Stuhr, 2022; Aikin & Talisse, 2022). This approach was adopted due to its flexibility, as it is not committed to a single philosophical or methodological framework (Islam, Khan & Baikady, 2022). The primary aim of this study was to develop practical, innovative solutions to real-world problems. Consequently, pragmatism naturally aligns with a mixed-methods design that incorporates both quantitative and qualitative research methods (Grover, 2015). This was essential because engineering innovations must address societal challenges, necessitating practical testing of innovations to complete the feedback loop consistent with Robbins' (2007) concept of the "Reflexive Engineer." Furthermore, when many participants with homogeneous characteristics engage in research, quantitative tools become invaluable (Powell, 2020).

The study involved both primary (including existing cases) and secondary research (including comparative case studies). Procedurally, it encompassed concurrent and partially sequential qualitative and quantitative data collection procedures for cross-verification and exploration, as well as analysis techniques for overall triangulation (Quant + Qual), as recommended by Doyle, Brady, and Byrne (2009) and Creswell (2014).

Data collection tools employed included a closed-ended survey questionnaire and key informant interviews (Creswell & Poth, 2016; Hafsa, 2019). Existing secondary data was gleaned from key national energy suppliers and relevant policymaking institutions for analysis. This data was crucial for input in the design of the model electrolyser presented in this chapter. Data was further processed using the Statistical Package for Social Sciences (SPSS). SOLIDWORKS® 2022 Software was employed for electrolyser design drawings, while the Global Solar Atlas v2.7 (June 2022) informed the sizing of the designed electrolyser in respect of projected optimum duration of solar radiation availability throughout the year. Global Solar Atlas v2.7 (June 2022) provides solar resource and photovoltaic power potential data globally. Thematic analysis was utilised for qualitative data analysis.

The integration of qualitative and quantitative data explained each other. A survey conducted with 98 participants provided quantitative data. Additionally, seven participants from key organisations involved in renewable energy and hydrogen, along with two community leaders and one academic expert in renewable energy, participated in key informant interviews, as presented in Table 1.2 in Chapter One.

A summary of research ethics is provided in Chapter One and further expanded in this chapter. Adherence to ethics is paramount in research. The protection of the dignity of research participants is integral. In this study, informed consent was sought, and the data provided was safeguarded (Akaranga & Makau, 2016). The foremost principle of any academic research is to do no harm; thus, the researcher was cognisant of ensuring that no physical, mental, or societal damage occurred to the participants and their environment (Dooly, Moore & Vallejo, 2017).

3.2.1. Experimental Design Part Of The Study

This study's experimental design fundamentally revolved around the exploration and implementation of a custom electrolyser that served as the core technological innovation for hydrogen production. The primary objective of this methodology is to delineate a clear framework that allowed reproducibility while outlining the design and operational parameters that underpinned the electrolyser's functionality within Mukaratigwa Village, Zimbabwe.

Recognising the importance of practicality in this research, an 8 kg target for daily hydrogen production capacity is grounded in empirical assessments of energy consumption patterns among selected households. This figure was established through qualitative research that involved six purposively sampled households utilising liquefied petroleum gas (LPG) for cooking and heating. Given that LPG is a prevalent energy source in rural Zimbabwe, analysing its consumption patterns provides valuable insights into the hydrogen needs that could effectively substitute this widely used fuel (Assabumrungrat et al., 2020).

A research design is essentially an action plan linking research questions to research conclusions (Chowdhury & Shil, 2021). Experimentation is intrinsically linked to technological development. In this case, it concerns electrolyser design and its application. As noted earlier, this experimental design is predicated on a specifically designed electrolyser. This electrolyser will offer relevant technical insights that contribute to a deeper understanding of cleaner energy technological innovations in practice using Mukaratigwa Village as a case study. To enhance these insights, ethnographic methods were employed to comprehend how innovation could address the sociological issue of energy poverty in a rural context (Cash, Stakovic & Storga, 2016).

3.2.2. Electrolyser Design And Equipment Sizing

The engineering design component of the research was earmarked for experimentation to fulfill the third objective of this study which sought to understand the role of hydrogen as an alternative energy source. This aspect particularly aids in analysing the potential role of hydrogen as an innovative energy vector in a typical African developing country. Acknowledging that, Africa generally faces similar challenges when it comes to energy poverty (Munro & Schiffer, 2019; Kesselring, 2017; Samarakoon, Bartlett & Munro, 2021).

While the researcher acknowledges that the Global South is not homogenous and that case studies may yield different results even within the same jurisdiction, energy poverty in Africa exhibits comparable traits. Technological interventions based on renewable resources aimed at countering global warming are also parallel (Baruch, 2008; Samarakoon et al., 2021; Forde, 2020).

Greener technological innovations in Africa are often hindered by limitations in investing resources towards research and development, thereby missing opportunities for mitigation and adaptation to combat both energy poverty and global warming (Adenle, Azadi & Arbiol, 2015). Other constraints, including inadequate infrastructure, limited research capacity, insufficient credit facilities, and lack of technology transfer impede the application of innovation in addressing energy poverty and climate change (Ibid).

To achieve the overall study objective, the researcher designed an electrolyser tailored to the needs of participants in the rural case study area of Zimbabwe. The nation consists of urban, peri-urban, and commercial farming regions, including A1 and A2 areas, as well as rural tribal trust lands/reserves

(Tatsvarei et al., 2022; Sato, 2022; Shonhe, 2019). Urban and peri-urban areas are better situated with existing infrastructure supporting electrical reticulation, while rural settings remain remote and under-prioritised for development. Rural areas are characterised by peasantry and vulnerability, with residents interacting more with their natural environment and ecosystems for their livelihoods and sustainability. Even though these agricultural communities coexist within the broader economy, they largely subsist on meager wages (Shonhe, 2019).

Historically, central governments have preferred urban settlements in their energy planning and development practices, a trend reflected in Zimbabwe. However, the recent policy reforms have emphasised a devolution agenda to counter the challenges posed by rural-urban migration. The choice of the remote Mukaratigwa Village justifies its selection as a case study, providing insights into the applicability of solutions developed in the Global North for use in the last mile of the development matrix. The renewal of the devolution agenda through the 2013 Constitution responds to post-independence efforts aimed at urbanising rural areas. However, earlier investments have faltered amid worsening and persistent poverty (Matsa & Masimbiti, 2014). This situation corroborates Scott's (1998) assertion that many initiatives developed in the Global South have not sustainably succeeded in addressing poverty challenges in those contexts.

The designed electrolyser can split water into hydrogen and oxygen using solar energy, and an appropriate hydrogen storage tank was also appropriately sized. The hydrogen produced was intended to establish supply and production sustainability and efficiency, thereby contributing to sustainable human and national development while ensuring the market production and accessibility of hydrogen remained viable.

The research was primarily guided by the Swansea University Electrolyser design manual, particularly the ESRI-RICE-H2NRG, following assembly instructions provided in Appendix E of this thesis. The design was crafted using SOLIDWORKS® 2022 Software, employing both bottom-up and top-down design methodologies to create the assemblies. Calculations integral to the design process were based on the number of hydrogen users in the village, set at 98 households, with further explorations discussed in subsequent sections.

3.2.2.1. Background to Electrolyser Sizing

As highlighted in the literature review in Chapter Two, this portion articulates the calculations undertaken to determine the optimal size and design of the electrolyser. It should be noted that the foundational formula for hydrogen production requirements was based on Wanjiku's (2011) original research that is principally a 0.8 kW electrolyser, significantly different from the 40 kW capacity utilised in this study. A detailed discussion on how Wanjiku's principles were adapted for this larger context ensures clarity and transparency. For ease of understanding, calculations were simplified, focusing exclusively on the most relevant aspects essential for grasping the design process.

The approach to sizing the electrolyser draws upon empirically observed consumption patterns of LPG among selected households. LPG served as a common cooking fuel in Zimbabwe, and establishing its consumption patterns allowed the study to derive equivalent hydrogen needs to effectively inform design capacity. Key parameters such as water-splitting efficiency, anticipated operational hours, and empirical data derived from local household energy demands underpinned the calculations to yield a daily output baseline of 8 kg hydrogen. The chapter emphasised how these calculations were tailored to the target community's realities, ensuring that the electrolyser design aligned with operational feasibility and environmental sustainability objectives central to this research endeavour. The following section clarifies the basis and relevance of the calculations, emphasising their adaptation to the larger electrolyser capacity applied in this study, and directs attention to their practical implications within Zimbabwe's socio-economic context, thereby enhancing the research methodology's overall narrative.

3.2.3. Rationale for the 8 kg Hydrogen Production Output

The decision to target an 8 kg daily hydrogen production output stemmed from operational assumptions regarding the electrolyser and the expected solar energy input in the area. This conservative estimate considers approximately 8 hours of usable solar radiation daily, supported by data that was derived through guidance from the Global Solar Atlas v2.7 (June 2022) software. Aligning this estimate with an average household size of six individuals who typically prepared three meals daily ensured that target production aligned with realistic rural cooking and heating demands.

3.2.4. A Clear Methodological Framework

The methodological approach blended practical engineering considerations with qualitative assessments. That was facilitated through a mixed-methods design encompassing quantitative and qualitative techniques. This promotes data triangulation and a comprehensive understanding of the practical implications of hydrogen production in the study area.

Data collected via closed-ended questionnaires from 98 participants was complemented by qualitative insights from key informant interviews with representatives from local energy organisations, community leaders, and a renewable energy academic expert. The integration of these methods and the mix of participants fostered a well-rounded perspective on local energy dynamics while ensuring diverse voices informed the research findings.

3.2.5. Data Analysis and Design Justification

Established parameters guided the engineering design and sizing of the electrolyser, including daily hydrogen output needs and solar energy potential substantiated by the Solar Atlas data. While earlier iterations of this methodology may have presented calculations ambiguously, the current approach underscored transparency in the processes that underpinned the electrolyser design.

Calculations associated with electrolyser sizing were a function of aligning hydrogen production needs with the empirically observed energy consumption patterns. The original formula referenced from Wanjiku (2011) for a smaller 0.8 kW electrolyser was rigorously adapted to fit the parameters of the larger 40 kW electrolyser deployed in this study. Clearly defining this necessary adaptation process ensures that the methodology remains relevant and comprehensible, enhancing replicability.

3.2.6. Contextualisation of the Study Area

The study area is a village located in the Global South and its choice was not a coincidence. In addressing the broader relevance of this study, it is crucial to define the term "Global South," particularly in relation to Zimbabwe's energy challenges. The Global South is commonly understood to include countries in Africa, Latin America, Asia, and parts of the Middle East, often characterized by various developmental constraints such as energy poverty, limited access to clean energy resources, and underdeveloped technological infrastructure. These regions typically experience significant disadvantages in economic development, health, education, and innovation.

This research's focus on Mukaratigwa Village exemplifies the unique challenges faced by communities in the Global South. This case study illustrates the pressing energy issues in Zimbabwe, where access to clean and sustainable energy remains elusive for many households. By situating the methodology within the practical energy needs and socio-economic realities of Mukaratigwa Village, this study establishes a robust foundation for exploring the potential of hydrogen as a viable, clean energy solution tailored to Zimbabwe's distinct context.

A significant challenge identified in the literature is the lack of published data regarding hydrogen consumption per household on a global scale. To determine the daily hydrogen requirements, this study relies on calculations based on the properties of hydrogen and the typical liquefied petroleum gas (LPG) consumption patterns of a purposively sampled group of six households that currently use LPG for cooking and heating. Given that LPG is widely utilised across African households, this study incorporates assumptions about the average household size estimated at six individuals who typically prepare three daily meals (one light meal and two heavy meals) and utilise additional energy for heating purposes.

As a result, this study anticipates the production of 8 kg of hydrogen daily, based on a conservative estimate that considers approximately 8 hours of usable solar radiation each day, with solar energy being the selected primary renewable source.

By grounding the study in the realities of the Global South, specifically within the context of Zimbabwe, this research aims to contribute meaningful insights into hydrogen's potential role in addressing energy challenges while also emphasizing the need for tailored energy solutions consistent with the region's socio-economic dynamics.

The Global Solar Atlas v2.7 (June 2022) software enriched the projection of solar resource and photovoltaic power potential data for Shurugwi District, directly guiding the design of the electrolyser. The same data also influenced the sample size of participants engaged in the research. This write-up section focuses on the electrolyser design, construction, and ancillary materials for a comprehensive deployable kit, including safety measures, storage, appliances (cookers), and utensils. The calculations supporting electrolyser sizing are presented below.

3.2.7. Parameters Used:

1. Power Requirements
2. Expected Output
3. Density
4. Temperature
5. Mass

3.2.8. Calculating Output:

Based on the assumptions regarding output, the calculations were carried out as further presented below:

i. The following parameters were used:

$$Density\ of H_2 \quad = 0.0837kg/m^2\ at\ 1atm$$

$$High\ Heat\ Value(HHV) \quad = 39.44kwh/kgH_2$$

$$Low\ Heat\ Value(LHV) \quad = 33.3kwh/kgH_2$$

$$Expected\ Output\ H_2/day = 8kgsH_2/8hrs$$

$$Electrolyser\ efficiency \quad = 85\%$$

ii. The power required in line with the above specifications was therefore:

$$Power\ (kw) = (H_2kg \times kwh/kgH_2\ )/(8hrs \times 0.85)$$

$$= (8kgs \times 33.3kwh/kgH_2\ )/(8hrs \times 0.85)$$

$$= 39.1764 \ldots . kw$$

$$\approx \mathbf{40} \boldsymbol{kw}$$

iii. Based on the assumption of having an output of $8kgs\, H_2/8hrs$, the output per hour therefore becomes $1\, kg/hr$.

iv. According to Harrison *et al*. (2010) in *Hydrogen Production Fundamentals and Case Study Summaries*, alkaline electrolysis cells operate between $200 - 600\, mAmp/cm^2$ with a voltage around 2.0V and temperature of 60 – 80 degrees Celcius.

v. From the observation that cells operate between 200mA – 600mA/cm^2, it was taken that the value that was slightly above average be determined and used in calculating the total amperage required for the $1634cm^2$ effective cell area of which the value was $600Amp/cm^2 = 0.6Amp/cm^2$ (refer to section 3.4 for clarification).

vi. With this fact, the total amperage given the area of electrode is 1634 cm^2, which therefore translates to;

$$Total\ amprage = Amp/cm^2 \times electrode\ effective\ area$$

$$= 0.6Apm/cm^2 \times 1634cm^2$$

$$= 735.3Amp$$

vii. To find the number of electrolyser Cells (N_c), the equation below as given in Wanjiku at al. (2011) was used:

$$H_2(kg/h) = ((2100g/molH_2 \times 3600s)/1000g) \times ((N_c I_{electy})/ZF)$$

$$= 1kgH_2/hr = 7.5816 \times \frac{N_c I_{electy}}{ZF}$$

Where; Z = the number of electrons transferred per mole of H_2O (Z=2)

F = 96485 C/mol or As/mol which is Faraday`s constant

By making Nc the subject of the formula, the equation becomes;

$$N_c = \frac{1kgH_2/hr \times Z \times F}{7.4816 \times I_{electy}}$$

$$N_c = \frac{1 \times 2 \times 96485}{7.5816 \times 7433}$$

$$= 25.96125 \ldots\ldots cells$$

$$\approx 26cells$$

viii. According to Wanjiku, Khan and Baraendse (2010) in *Analytical Sizing of an Eletrolyser for Small Scale Wind Electrolysis Plant*, a cell with 100 cm^2 using $0.4 - 0.8Amp/cm^2$ average of 0.52 Amps and 11 cells * 2.2 ≈ 24 volts.

ix. Using the area ratio, it is noted that an area of 1634 cm^2 which represents one cell of the present design is equivalent to 16.34 cells ≈ 16 cells of the 100 cm^2 area cell configuration which requires 1.25kw of power.

x. With this fact, the voltage that will be required to power a 1634cm^2 cell is supposed to be

$$26 \times 1.48V = 38.48volt\ (\approx 48V)$$

3.3. Electrolyser Technical Specifications

Table 3.1 presents the technical specifications for the electrolyser size adapted in this study. As noted earlier, the ESRI-RICE-H2NRG design was guided by the deployable electrolysis system assembly instructions provided in Appendix E.

Table 3.1: Proposed Technical Specifications

Stack size	500 x 500 x 150.8 mm
Effective cell area	$430mm \times 380mm = (1634cm^2)$
Number of cells	$\mathbf{26\ cells}$
Membrane	$2mm\ Zirfon\ per\ UTC\ 500$
Electrode material	$0.9MM\ 316\ Stainless\ steel\ sheet$
Electrolyser current range	$200mA - 500\ mA/cm^2$
Voltage range	$48\ Volts$
Electrolyte	$Potassium\ Hydroxide$
Hydrogen output	$1kg\ H_2/hr$
Operating Temperature	$15 - 85\ Degrees\ Celcius$

These technical specifications reflect a comprehensive appreciation and analysis of challenges observed in the ESRI-RICE-H2NRG, particularly concerning the mild steel electrode plate surface's smoothness, which hinders the desired chemical reaction and slows down the adsorption process critical to catalytic processes (Jackson, Granndall & Bozack, 2015; Dąbrowski, 2001). Surface roughness has a pronounced impact on electrical conductivity and catalytic activity.

3.4. Basis Anchoring Electrolyser Sizing

The design and sizing of the electrolyser are crucial components of this study, ultimately informing hydrogen production's viability in rural Zimbabwe. To ensure clarity and replicability in the methodology, this section explains the calculation process and rationale behind key design choices. A critical parameter for electrolyser design is the effective cell area, specified as 1634 cm^2. This figure's thorough and systematic derivation is essential, as it represents the surface facilitating essential electrochemical reactions required for hydrogen production.

The effective cell area of 1634 cm^2 was influenced by the anticipated energy demands of the local community and informed by insights gathered from previous models. The effective cell area of 1634 cm^2 has been carefully derived from the assembly and specifications as outlined in the ESRI-RICE-H2NRG deployable electrolysis system assembly instructions, specifically Appendix E, which describes the components and their dimensions. Each electrode measures 500mm x 500mm, yielding an individual surface area of 250,000 mm^2 or 250 cm^2 (ESRI-RICE-H2NRG, 2023). However, adjustments for active versus inactive areas within the assembly result in an effective area of 1634 cm^2. This figure accounts for the contributions of spacers and alignment mechanisms that facilitate the design's electrochemical reactions.

The specification of 48V serves a crucial role in maximizing efficiency and minimizing resistive losses within the electrolyser. According to the assembly instructions, stacks designed for voltages above 24V—such as 48V—require longer compression bolts to ensure structural integrity and maintain optimal alignments of the electrodes (ESRI-RICE-H2NRG, 2023). Operating at 48V allows for improved efficiency in the electrolysis process. As noted by Wanjiku et al. (2011), higher voltage electrolyzers can operate more efficiently, leading to reduced current draw for a given power output, thereby addressing the energy demands of the local community (Harrison et al., 2010). This operational voltage is consistent with findings in the literature regarding alkaline electrolysis cells, which typically exhibit optimal performance in the range of 2.0V for each cell (Harrison et al., 2010). Thus, the adopted voltage aligns with both practical application standards and the specified needs of the electrolyser design.

3.4.1. Methodological Framework for Simulations

This study utilised SOLIDWORKS® 2022 software to create detailed design schematics of the electrolyser. It ran simulations based on standardised electrolysis parameters such as operating voltage, current density, temperature, and pressure, all aligning with industry standards for alkaline electrolysis (Harrison et al., 2010). The methodology involved an iterative design process, where adjustments to physical attributes, like cell dimensions, were made to optimise hydrogen output. Rigorous protocols for simulation setup, including input parameters and validation steps, were documented to enhance reproducibility.

3.5. Hydrogen Production Parameters vs LPG

The calculation of hydrogen production hinged on established calorific values for LPG and hydrogen, serving as comparative benchmarks for energy requirements. Observed LPG consumption patterns among six purposively sampled households provided qualitative data about energy usage in rural settings. Average LPG consumption was translated into equivalent hydrogen needs, establishing a framework for determining the daily output necessary for 98 households, subsequently informing the electrolyser's design capacity targeting 8 kg of hydrogen production per day.

3.6. Validity of the Calorific Value Approach

The approach relying on calorific values necessitates careful consideration of its validity. Heating values per gram of hydrogen (33.33 kWh/kg) and LPG (approximately 13.6 kWh/kg) were employed in conversions for assessing energy equivalence during transitional use. This comparative approach is supported by research indicating that comparable fuel types provide reasonable approximations for user needs when transitioning to hydrogen technologies (Wanjiku et al., 2011).The calorific values utilised—33.33 kWh/kg for hydrogen and 13.6 kWh/kg for LPG are established figures widely accepted in combustion science and energy economics, which serve as a foundation for comparative energy analyses (Liu et al., 2010; Hwang et al., 2017).

This validity is attributed to the rigorous derivation of these values through empirical research. For instance, hydrogen's high calorific value can be evidenced by several studies demonstrating its potential as a clean energy carrier, while LPG has an established heating value derived from various combustion tests (Rosa et al., 2015; Smith et al., 2021).

However, it is crucial to recognize the limitations of relying solely on calorific values for this analysis. The overall efficiency of the conversion systems, the distinct combustion properties of each fuel, and broader environmental impacts must be taken into account to provide a comprehensive evaluation (Dincer & Acar, 2018). For instance, while calorific values give a baseline for energy content, they do not encompass factors like the thermal efficiency of burners or the operational safety in practical applications (Huang et al., 2020).

As such, while calorific values serve as a foundational starting point for analyzing energy equivalence, further research that incorporates efficiency factors and real-world experimental data will be necessary to substantiate the conclusions regarding the practicality of hydrogen as a viable substitute for LPG (Mabeshar & Khan, 2019).

3.6.1. Detailed Calculation Steps

1. **Required Power Calculation:** Based on expected energy requirements and production targets.

2. **Current Density and Voltage Application:** Following standards set by Harrison et al. (2010) for alkaline electrolysis, where cells operate at 200-600 mAmps/cm² with an average voltage of around 2.0 V.

3. **Calculate Total Current Capacity:** The targeted current density translates to the total amperage required for a 1634 cm² effective cell area: Total Current = {Effective Area} × {Current Density}, in this case, Total Current = 1634 cm² × 0.6 A/cm² = 980.4 A.

4. **Electrolyser Cell Sizing:** Adherence to equations from Wanjiku et al. (2011) to calculate the necessary number of cells based on electron transfer:

   - The Faraday constant (F = 96485 C/mol) yields: [N_c = Q / (Z × F)]

5. **Voltage Assessment:** Understanding voltage necessity based on cell configurations:

   - Revealed that with 16 cells from prior models, power demand scales up to manage denser electrolyte flow effectively.

3.6.2. Addressing Technical Adaptations and Challenges

The discussion of the electrolyser's specifications must address adaptations made in response to identified challenges, such as improving electrode surface conditions to enhance catalytic processes. The implications of roughness on surface area and catalytic activity must be considered based on literature detailing how surface characteristics influence adsorption and subsequent electrochemical processes (Jackson et al., 2015; Dąbrowski, 2001).

3.7. Questionnaire Development Process

Developing and implementing the survey questionnaire constituted a pivotal aspect of this research, which aimed to assess community perceptions regarding hydrogen as a viable energy source for household heating and cooking in rural Zimbabwe. This section delineates the methodologies for constructing the questionnaire, identifying study groups, ensuring ethical compliance, and establishing safety measures.

The questionnaire was developed using a systematic approach, employing the following methodologies:

- ***Literature Review:*** A preliminary review of existing literature and survey instruments related to energy perceptions informed the development of relevant questions, ensuring that the instrument is grounded in contemporary research (Creswell, 2014). Other existing questionnaires were critically evaluated for applicability and effectiveness leveraging established instruments in energy studies.

- ***Pilot Testing:*** The initial questionnaire was pre-tested with a small sample comprising local community leaders and members familiar with energy issues. Feedback was utilised to refine clarity, applicability, and reliability. This step was crucial for improving questions to yield valuable and comprehensible data (Dillman et al., 2014).
- ***Structured Format:*** The final instrument comprised a mix of closed and open-ended questions that captured quantitative and qualitative data. This hybrid approach facilitated a comprehensive understanding of participant views while allowing for richer responses regarding nuanced perceptions of hydrogen energy.

3.7.1. Identification of Participant Groups

Participants for the study were segmented into two primary groups:

1. **Community Members:** The first group consisted of participants from Mukaratigwa Village, Shurugwi District. Through community outreach strategies and local leadership, 98 households were identified for the study, ensuring representation across varying demographics. Each household contributed one individual to avoid response bias, employing a cluster sampling technique for diverse insights.
2. **Key Organizations and community participants:** The second group included representatives from 12 organizations engaged in hydrogen production, distribution, and potential use. Also, 7 participants from the community leadership were included in the study. Identification through networking and prior collaborations ensured the gathering of key insights from experts, which contributed to robust content for practical applications. Two focus group discussions were also carried out, in addition to three feedback workshops and two seminar discussions.

3.7.2. Ethical Considerations

Adherence to ethical standards was paramount throughout the research process. Ethical clearance was obtained from relevant authorities, including the Ministry of Local Government and the Environmental Management Agency (EMA). Participants were provided clear information regarding the study's purpose, with informed consent sought from all individuals involved. Ethical protocols also addressed confidentiality and data protection issues. Participants' identities were anonymised in reporting to safeguard against potential repercussions from their involvement (Creswell, 2014).

3.8. Safety Protocols and Risk Management

Safety considerations were embedded within the study methodology to ensure the well-being of all participants engaged in hydrogen handling. Key safety protocols included:

- ***Butyl Rubber Bags for Gas Storage:*** Hydrogen had to be stored in butyl rubber bags designed for low to medium pressures (housed in containerized units), typically not exceeding 30 bar. These bags were chosen for their impermeability to hydrogen and durability under appropriate pressures for safe handling and storage (MAHYTEC, 2016).
- ***Safety Distancing Guidelines:*** Guidance on safety distances was established based on existing engineering standards and safety best practices (Khan et al., 2013). Operations were conducted at a minimum distance of 15 meters from populated areas to minimise exposure to risk from potential leaks.
- ***Hydrogen Leak Detection:*** Hydrogen alarms and detectors were to be integrated into the design to continuously monitor for leaks and ensure prompt notifications for hazardous conditions (Amyotte, 2013).
- ***Safety Training:*** All personnel had to receive training in hydrogen handling, emergency response, and safe operational practices based on international standards (ISO 45001 and 14000). Such training emphasised recognising and responding to potential hazards associated with hydrogen.
- ***COVID-19 Protocols:*** Given the pandemic's context during the research timeline, necessary health and safety protocols were observed to minimise risk, ensuring the research environment remained safe and compliant with the COVID-19 regulations that prevailed during the time of the study (World Health Organization, 2020).

This methodological framework underscores the importance of a well-structured questionnaire, effective participant identification, rigorous ethical standards, and comprehensive safety protocols in exploring hydrogen as a viable energy solution in rural Zimbabwe. Enhancing clarity and detail in this section establishes a replicable methodology that meaningfully contributes to the discourse surrounding sustainable energy solutions.

3.9. Electrolyser Weight Calculations

To determine the electrolyser's overall weight, which is key for compatibility and handling considerations, the following calculations ensued:

$$Weight\ of\ 27\ electrodes = 0.5m\ \times 0.5m \times (0.001 \times 27)m \times 7800\ kgs/m^3$$

$$Weight\ of\ 27\ electrodes = \mathbf{52.65kgs}$$

$$Weight\ of\ water = 0.104m \times 0.38m \times 0.43m \times 999.77\ kgs/m^3$$

$$Weight\ of\ electrolyte = \mathbf{16.9557kgs}$$

$$Weight\ of\ Butyl\ rubber = 0.0967m^2 \times 0.104m \times 920\ kgs/m^3$$

$$Weight\ of\ Butyl\ rubber = \mathbf{9.252256 kgs}$$

$$Weight\ of\ Zirfon\ membrane = 0.48m \times 0.48m \times (0.002 \times 26)m \times 920\ kgs/m^3$$

$$Weight\ of\ Zirfon\ membrane = \mathbf{11.022336 kgs}$$

$$Weight\ of\ Acrylic = 0.62 \times 0.62 \times 0.03 \times 920\ kgs/m^3$$

$$Weight\ of\ Acrylic = \mathbf{10.60944 kgs}$$

$$Weight\ of\ Stainless\ steel\ end\ plates = \mathbf{38.4378 kgs}$$

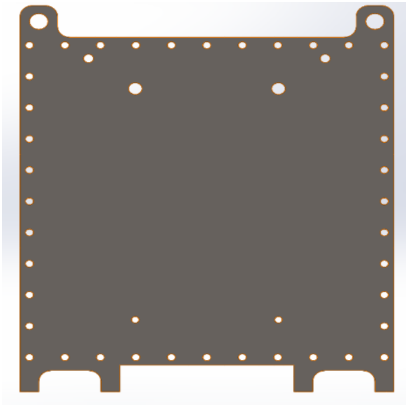
$$Weight\ of\ bolts\ \&\ nuts = \mathbf{5 kgs}$$

Table 3.2: Total Weight of Electrolyser

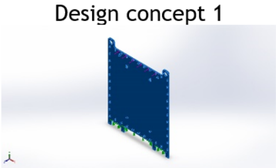
Material	**Weight (Kgs)**
27 Electrodes	52.65
Electrolyte	16.9557
Butyl Rubber	9.25223
Zirfon Membrane	11.022
Acrylic	10.609
Stainless steel end plates	38.4378
Bolts and Nuts	5
Total Weight	**143.9273Kgs**

3.10. Stainless Steel End Plate Design

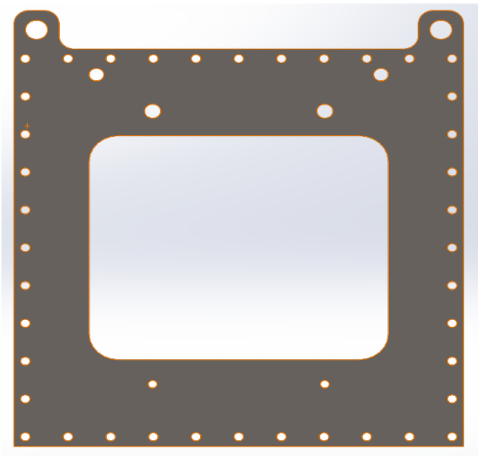
The standard ESRI-RICE-H2NRG design includes acrylic end plates, which are brittle and pose a challenge regarding the electrolyser's physical strength. To mitigate this, stainless steel reinforcement plates were proposed, maintaining the system's anti-corrosive properties. The strength of the end plate supporting the acrylic end covers was ascertained through design concepts analysed using SOLIDWORKS® 2022 Software, with concept number three emerging as the optimal design. Figure 3.1 below illustrates the three concepts for end plate design.



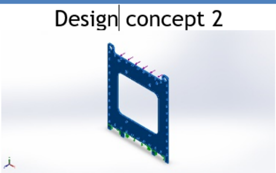
Design Concept 1

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Design concept 1 	Solid Body	**Mass:30.3408 kg** **Volume:0.0037926 m^3** **Density:8,000 kg/m^3** **Weight:297.34 N**	**C:\Users\chiny\OneDrive\Documents\sample end plate 1.SLDPRT** Dec 4 14:21:29 2022

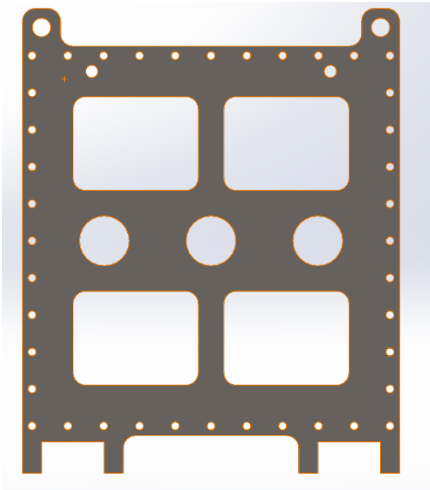
Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 55	2.864e-01mm Node: 72



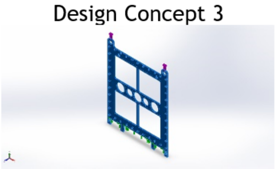
Design Concept 2

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Design concept 2 	Solid Body	**Mass:19.2189 kg** **Volume:0.00240236 m^3** **Density:8,000 kg/m^3** **Weight:188.345 N**	**C:\Users\chiny\OneDrive\Documents\electrolyser end plate metal.SLDPRT** Dec 4 13:36:04 2022

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	6.738e-01mm Node: 158



Design Concept 3

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
Design Concept 3 	Solid Body	Mass:14.7224 kg Volume:0.0018403 m^3 Density:8,000 kg/m^3 Weight:144.279 N	C:\Users\chiny\OneDrive\Documents\proposed end plate design 2.SLDPRT Dec 13 12:47:57 2022

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	6.869e-01mm Node: 92

The total weight reduced in the process in presented as Figure 3:1 below:

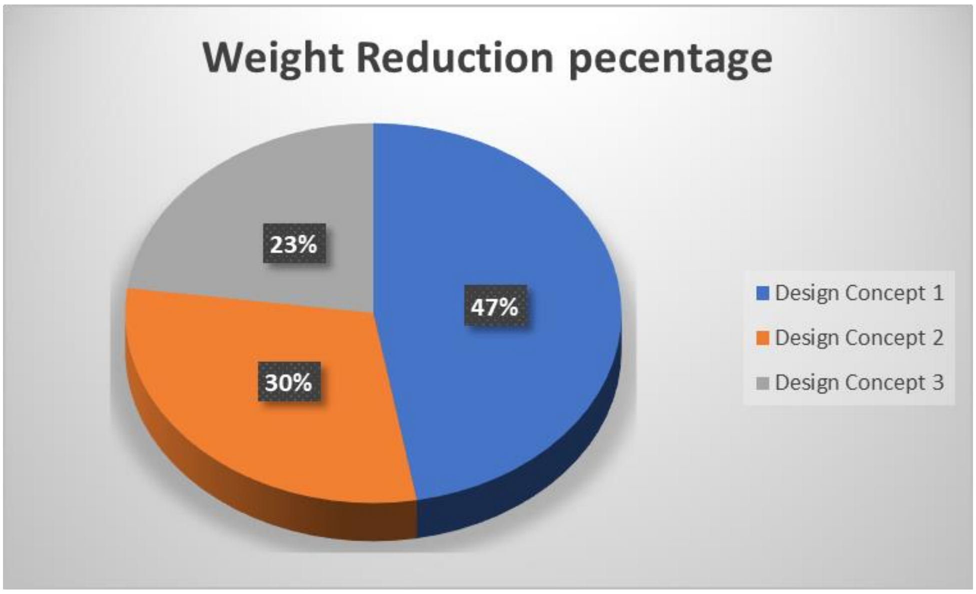
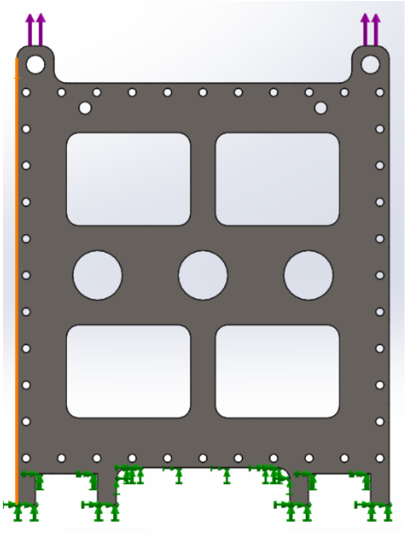


Figure 3.1: End Plate Design Concepts 1-3 (Source: Author's Compilation, 2024).

According to the analysis chart within Figure 3.1, the weight has effectively been reduced by 77% from the original concept based on previous Swansea prototype designs. Additionally, results from

SOLIDWORKS® 2022 Software simulations confirmed that all design concepts met the required specifications and bore the necessary torque without warping. The difference between the design concepts is in their net weight; hence the designer (Researcher) opts to use design concept 3 with the least weight, which will positively reduce the total weight of the electrolyser by approximately 25kgs

The anchor points' load-carrying strength for the chosen design concept was also analysed using SOLIDWORKS® 2022 Software, determining a 0.06 mm elasticity which is negligible under dynamic loading as simulations were conducted under static conditions or fixed geometry loading. The loading and elongation results are shown in Figure 3.2 below:



Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 1	6.404e-0.06mm Node: 14500

Figure 3.2: Load carrying capacity (Author's Compilation, 2024).

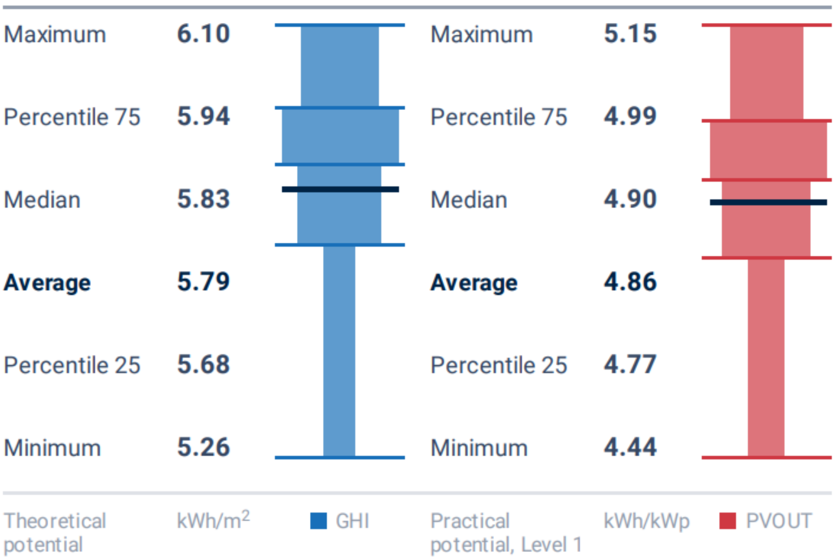
Utilising Global Solar Atlas v2.7 (June 2022) software and focusing on Shurugwi, the designer obtained photovoltaic power output for the entire year as illustrated in Figure 3.3 below.

AREA INFO

Map data (min-max range)

Specific photovoltaic power output	PVOUT	**4.50**	—	**4.92**	kWh/kWp
Direct normal irradiation	DNI	**5.28**	—	**6.11**	kWh/m^2
Global horizontal irradiation	GHI	**5.34**	—	**5.79**	kWh/m^2
Diffuse horizontal irradiation	DIF	**1.75**	—	**1.88**	kWh/m^2
Global tilted irradiation	GTI	**5.72**	—	**6.20**	kWh/m^2
Optimum tilt of PV modules	OPTA	**22**	—	**24**	°
Air temperature	TEMP	**20.1**	—	**23.7**	°C
Terrain elevation	ELE	**319**	—	**1532**	m

SUMMARY STATISTICS



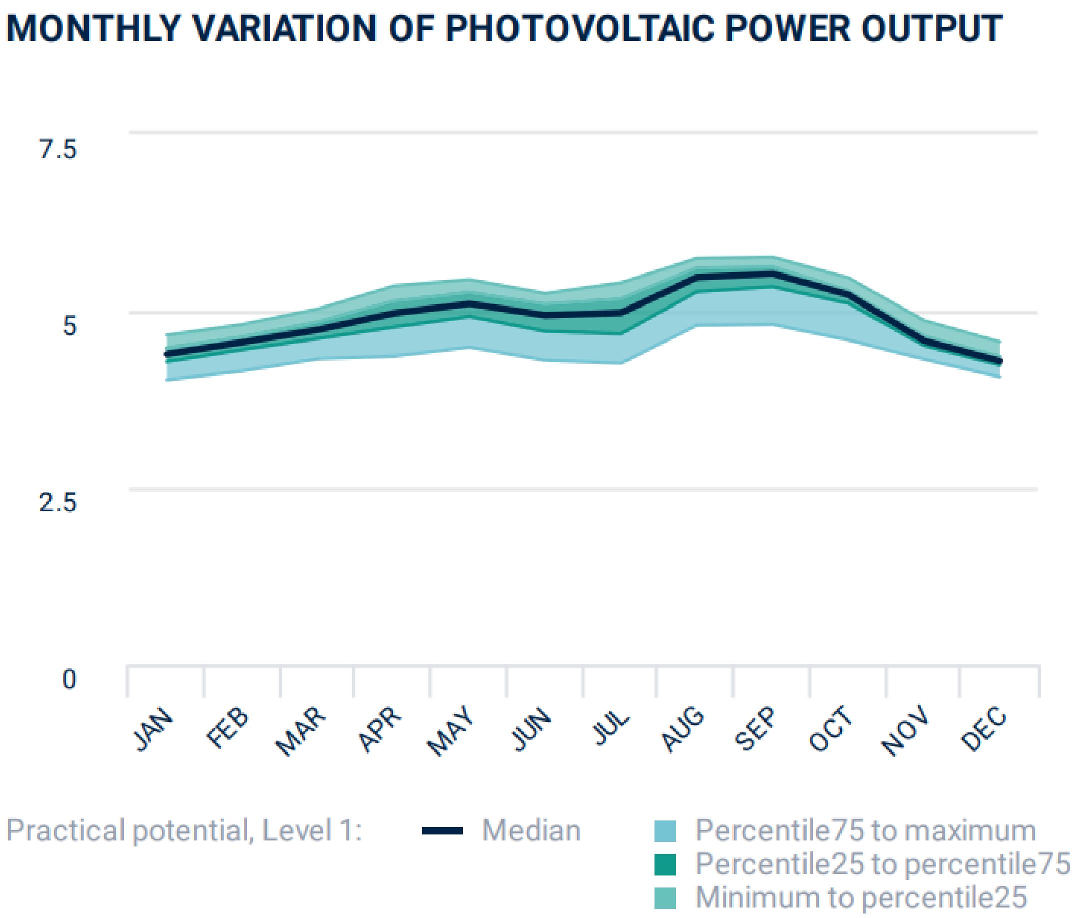


Figure 3.3**:** Photovoltaic Power Output per year.

The overall project cost was calculated as presented in Table 3.3 below.

Table 3.3: Total cost for the project

HYDROGEN ELECTROLYSER BILL OF MATERIAL AND EQUIPMENT (USD)				
Item No	**Material/Item**	**Quantity**	**unit price**	**total price**
1	10mm Acrylic (laser cut) 600mm * 620mm	2	40.7	81.4
2	0.9 mm 316 SST 500mm * 500mm including laser cutting	27	130	3510
3	2mm butyl rubber (480mm * 480mm)	54	50.86	2746.44
4	Zirfon membrane (480mm * 480 * 2mm)	27	40.5	1093.5
5	10mm stainless steel (600mm * 620mm) (optional)	2	25.6	51.2

6	M8 stainless steel nuts	84	0.75	63
7	M8 * 1metre stainless steel studs (for 42 holes)	25	12	300
8	8mm stainless steel washers	84	0.25	21
9	8mm gas outlet tubes * 6 meters	2	40.6	81.2
10	8mm electrolyte feed tubes * 6 meters	2	40.6	81.2
11	Storage cylinder (butyl rubber lined) 700Bar min pressure	3	190	570
12	Electrolyde circulation pump (5-12V) (4:2.4m head)	1	80	80
13	Solar panels 320W photovoltaic& accessories	125	150	18750
14	Adhesive bond * 1 litre	2	14	28
15	Wind turbines and accessories	4	400	1600
16	Container 20 foot (engineered to suit application)	1	2000	2000
17	6mm stainless steel studs* 1meter	2	12	24
18	Non-return valve 1"BSP 0-25 bar	2	9	18
19	Electrofusion fitting 25mm-32mm 0-16bar	4	4	16
20	Flashback arrester 1"45mbar opening pressure	4	5	20
21	Solenoid valve 25mm (1”) BSP 24V EODM	2	22	44
22	Stainless steel ball valve 1" BSP 0-6Bar	2	5	10
23	Tank exit butterfly valve HDPE	2	8	16
24	100L Scrubber	2	45	90
25	1000L plastic water container	1	80	80
26	Drip tray	1	13	13
27	PVC Pipes and connectors	20	6	120
28	Burner and accessories	30	45	1350

29	pressure gauge	2	15	30
30	2000mm double channel iron 100mm*50mm	5	13	65
31	1250mm double channel iron 100mm*50mm	4	13	52
32	562mm double channel iron 100mm*50mm	6	13	78
33	859mm angle iron 100mm*50mm	6	11	66
	GRANT TOTAL	**US$33,148.94**		

3.11. Ascertaining Amount Of H_2/DAY

I. To ascertain the amount of hydrogen gas required for preparing three meals for a family of six daily, a practical approach was adopted, involving three families that used LPG (propane) stored in 5 kg capacity gas tanks.

II. It was observed that 5 kg of LPG sufficed for preparing three meals daily over a week (7 days) for an average family of six.

III. From this observation, it can be deduced that approximately 0.7142 kg of LPG is required to prepare three meals daily for a family of six.

IV. According to *the College of the Desert Module 1*: Hydrogen Properties, the calorific values of hydrogen and propane are presented in Table 3.4 below.

Table 3.4: Calorific values of hydrogen and propane

	Density Kg/m^3	**HHV Calorific Value MJ/Kg**	**LHV Calorific Value MJ/Kg**
HYDROGEN	0.090	141.7	120.0
PROPANE	0.537	49.3	45.5
BIOGAS	0.537	50.0	45.0

V. For propane, the daily requirement is derived to be 0.7142 kg. **Therefore, using the propane calorific value, the energy required per day becomes:**

$$0.7142 \text{ kg} \times 45.5 \text{ MJ/kg} = 32.4961 \text{ MJ/day.}$$

VI. Dividing 141.7 MJ/kg H_2 by the daily energy requirement of 32.4961 MJ indicates that approximately 1 kg of hydrogen would last about four days. Hence, 0.25 kg H_2 will be required daily.

VII. Considering practical applicability, a safe production target will be approximately 0.25 kg H2/day.

3.12. Sizing Hydrogen Gas Storage Tank For 100 Kg Capacity

According to MAHYTEC (2016), when compressed, hydrogen's density at 35.0 MPa is about 23 kg/m³, while at 70.0 MPa, it is around 38 kg/m³; this results in an energy density of 767 kWh/m³ (at 27°C, 35 MPa).

When sizing the hydrogen gas storage tank, the following parameters were considered:

- Tank inner volume
- Operating pressure in bar or pascal
- Mass of hydrogen stored at the operating pressure in kg
- Operating temperature range in °C
- Maximum allowable pressure in bars
- Net mass of the tank in kg

MAHYTEC (2016) states that steel vessels are commonly used for high-pressure gas compression storage, often with operating pressures as high as 700 bars. However, steel is not ideal for hydrogen storage. The diffusion of hydrogen into steel leads to embrittlement failure, particularly when vessels undergo frequent charging and discharging. This embrittlement issue can be resolved by utilising vessels made of composite materials consisting of polythene or carbon fibre and epoxy resin featuring a thin aluminium liner.

Compressed hydrogen is to be stored in tanks comprising a polymer liner and a composite structure that supports the mechanical forces, as noted by https://www.sciencedirect.com.

According to the European Integrated Hydrogen Project (EIHP; ref: www.eihp.org), compressed hydrogen gas storage vessels can be classified into four types:

- **Type I:** All-metal cylinder;
- **Type II:** Load-bearing metal liner hoop wrapped with resin-impregnated continuous filament;
- **Type III:** Non-load-bearing metal liner axial and hoop wrapped with resin-impregnated continuous filament, and;
- **Type IV:** Fully wrapped composite cylinder with a metal liner acting as the hydrogen permeation barrier.

Type III vessels feature a fully wrapped composite cylinder with a metal liner as a barrier against hydrogen permeation. This aluminium liner mitigates embrittlement concerns while contributing over 5% to the mechanical resistance. Type III composite tanks are reliable for pressures up to 450 bar, although challenges persist when pressure cylinder tests are conducted at 700 bars.

At 700 bar pressure (700 times normal atmospheric pressure) hydrogen exhibits a 42 kg/m³ density, compared to 0.090 kg/m³ at standard pressure and temperature (https://energies.airliquide.com). At this pressure, 5 kg of hydrogen can be stored in a 125-liter tank. MAHYTEC (2016) asserts a 300 L internal volume can store around 10 kg of hydrogen at 500 bar. Design pressure for 5 Nm³/hour (0.45 kg/h H_2) is calculated at 22 bar, including safety factors according to the RES2H2 Project.

MAHYTEC (2016) indicates that an 850-liter tank can contain about 4.2 kg H_2 at 60 bar (https://www.mahytec.com). 700-bar pressure with a 42 kg/m³ density takes about 16.66 bar to compress 1 kg of hydrogen (approximately 17 bar). Therefore, for a capacity of 10 kg H_2, approximately 170 bar of maximum pressure is necessary. Consequently, the tank required for 10 kg hydrogen storage must withstand a pressure of 170 bar without failure.

- **Buffer Storage:** For hydrogen buffer storage of 100 kg H_2, three 700-bar pressure tanks capable of accommodating 42 kg H2/m³ each will be needed. The tank design must be cylindrical to prevent buckling and deflection under pressure and should feature butyl rubber lining to mitigate permeation risk. Each tank is expected to have a volume of 1 m³, resulting in a 1-meter diameter and a length of 1.28 meters.
- **Tank Design Considerations**: The design of tanks for hydrogen storage, especially at pressures around 700 bar, typically involves robust engineering principles. They are often constructed from materials that provide high strength-to-weight ratios, such as carbon fiber composites or high-strength steel (Müller et al., 2014). If butyl rubber is employed, it would typically serve more as a protective liner to reduce permeation rather than bearing the structural load of high-pressure gas storage (Wang et al., 2021).

3.12.1. Cognizant that:

Butyl rubber is known for its excellent impermeability to gases, including hydrogen, making it suitable for specific applications involving hydrogen storage. However, when it comes to high-pressure hydrogen storage, there are several important considerations to keep in mind:

3.12.2. Properties of Butyl Rubber

- ***Pressure Limitations***: Butyl rubber is generally not used for high-pressure gas storage like that at 700 bar. While butyl can withstand moderate pressures, its structural integrity and resilience significantly decrease at high pressures. Typically, composite materials (like carbon fiber reinforced composites) or metals (like steel or aluminum) are used for high-pressure hydrogen storage tanks.

- ***Permeation:*** While butyl rubber does provide good permeability resistance to hydrogen, at high pressures, the permeation rates can still become significant over time, potentially leading to gas losses.

- ***Mechanical Strength:*** Rubber materials, including butyl, are not designed to withstand the mechanical stresses of high-pressure environments, such as 700 bar. They can deform under pressure, leading to failure or loss of containment.

3.12.3. Appropriate Materials for 700 Bar Hydrogen Storage

For hydrogen storage at **700** bar the following materials are typically recommended:

- ***Composite Materials:*** These tanks are often made from a combination of a metal liner surrounded by carbon fiber-reinforced polymers. This design allows for high strength-to-weight ratios and resistance to deformation.

- ***Metal Tanks:*** High-strength steel or aluminum tanks are used because they can handle high pressures while maintaining structural integrity.

Notably, while butyl rubber has beneficial properties for low-pressure applications, it is **not appropriate** for storing hydrogen at **700 bar** due to its limitations in pressure resistance and potential for failure. For high-pressure hydrogen storage applications, one should consider using composite or metal tanks specifically designed and tested for such conditions (stage I & II below).

Consequently, a Two-stage Approach is recommended to be employed as follows:

I. FIRST - Design Specifications

- **Type**: Cylindrical tanks
- **Material**: Butyl rubber lining to mitigate permeation (or composite material lining)
- **Design Pressure**: 700 bar
- **Volume per tank**: 1 m^3
- **Diameter**: 1 meter
- **Length**: 1.28 meters
- **Total Number of Tanks**: 3
- **Total Storage Capacity**: (3 times 42 = 126 kg) (which exceeds the required 100 kgH_2, providing a buffer).

Summary Design Storage Tank Considerations/Calculations:

The study requires **three 700-bar cylindrical pressure tanks, each with a volume of 1 m^3**, having a diameter of **1 meter** and a length of **1.28 meters**. The tanks may be lined with butyl rubber to minimise the permeation of hydrogen (stage I). This design effectively meets and slightly exceeds this study's storage needs of **100 kg H_2**.

II. Final Storage Tank Design Considerations for 700 bar Hydrogen Storage

Design Overview

The proposed design for hydrogen storage (with safety and sustainability considerations) consists of **one high-pressure composite tank** with a capacity to store hydrogen at 700 bar.

Key Design Specifications:

1. **Type of Tank**:
   - ***Composite Pressure Vessel:*** A metal liner (typically aluminum or steel) surrounded by carbon fiber reinforced composite to withstand high pressures while minimising weight.
2. **Capacity**:
   - ***Storage Volume:*** A minimum of **1 m^3** required to accommodate over **100 kg** of hydrogen.
   - ***Hydrogen Density:*** At 700 bar, hydrogen density is approximately **42 kg/m^3**.
   - ***Calculated Capacity:***
     - Total Hydrogen Storage Each Tank: 42 kg
     - Number of tanks needed for 100 kg = 2.38
     - **Total Tanks Required**: At least **3 tanks** if each is 1 m^3, providing a total storage capacity of **126 kg**.
3. **Tank Geometry**:
   - ***Shape:*** Cylindrical design to prevent buckling and deflection.
   - ***Diameter:*** 1 meter.
   - ***Length:*** Approximately **1.28 meters** per tank, based on a 1 m^3 volume calculation.
4. **Material**:
   - ***Lining:*** Metal liner (steel or aluminum).

- ***Outer Layer**:* Composite (carbon fiber or fiberglass) for strength and lightness.

5. **Pressure Rating**:
   - ***Operating Pressure**:* Designed to contain hydrogen at **700 bar**.
   - ***Safety Features**:* It includes pressure relief valves and structural reinforcements to handle over-pressurisation and thermal stresses.
6. **Permeation Control**:
   - The metal liner minimises permeation loss, effectively addressing concerns with gas retention.
7. **Safety Standards**
   - Comply with relevant industry standards for high-pressure gas storage, such as ISO 11119 and ASME codes.
8. **Additional Considerations**:
   - ***Thermal Insulation**:* Implement to manage temperature fluctuations affecting hydrogen pressure.
   - ***Monitoring Systems**:* Integrate sensors for pressure, temperature, and potential gas leaks to ensure safe operation.

The final design position is for **three composite pressure tanks**. Each with a capacity of **1 m^3**, capable of safely storing hydrogen at **700 bar**. This design approach ensures optimal safety, efficient storage, and effective management of hydrogen's unique properties.

3.13. THE DESIGNED AND SIZED ELECTROLYSER

The following (Figure 3.4) illustrates the final proposed model electrolyser designed and sized. Key points to consider before construction include potential issues with the positioning and sealing of the electrode, membrane, and butyl rubber gaskets. That could lead to leaks during electrolyser operation. It is also essential to ensure that the membrane and electrode are adequately secured to allow electrolyte flow without obstructing catalytic reduction.

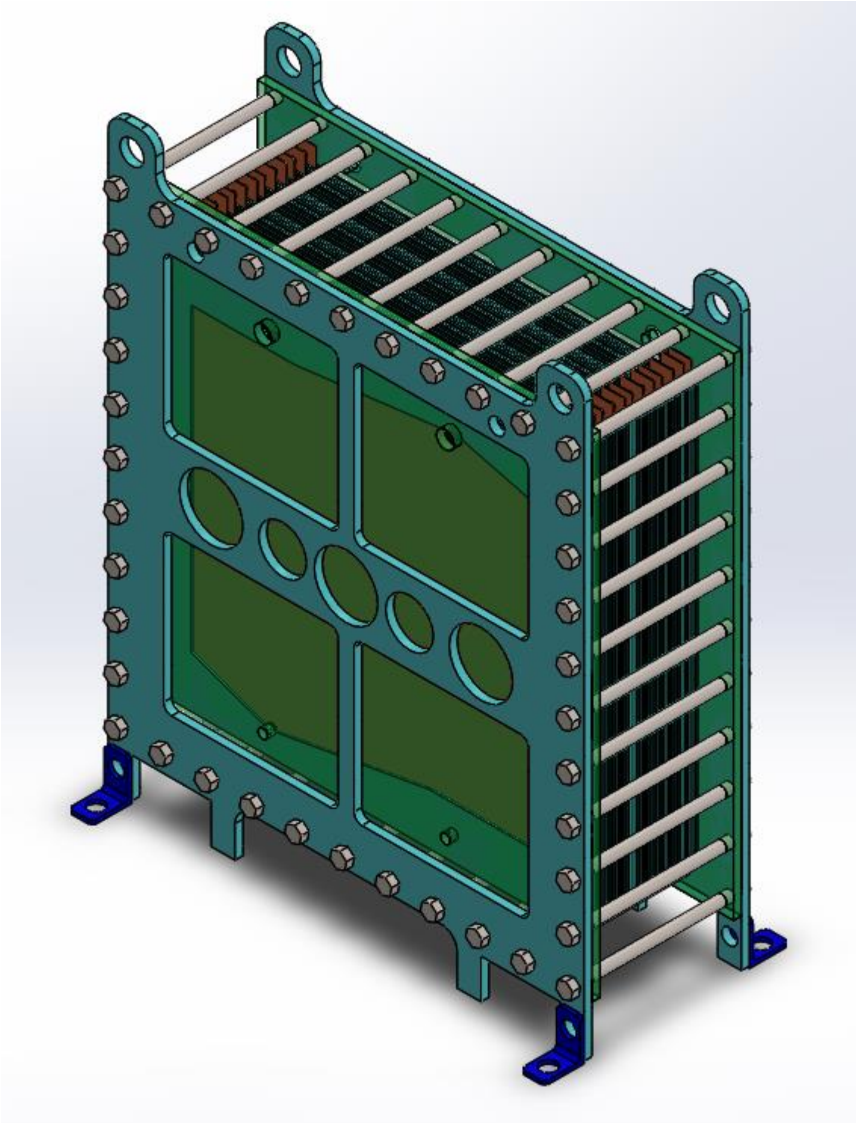


Figure 3.4: Final Proposed Model Electrolyser (Source: Author's Compilation, 2024).

Figure 3.4 above illustrates how the final designed electrolyser would look.

3.14. THE ETHNOGRAPHIC PART OF THE STUDY

The ethnographic technique is a research methodology used in anthropology, sociology, and other social sciences to study human cultures, behaviours, and interactions. It involves immersive, long-term fieldwork to gather in-depth, contextual data. In this context of interdisciplinary research it is derived from life history encompassing an in-depth study of community experiences including the researcher's individual life exposure as he grew up within the study communal area. Key ethnographic principles include:

- Participant Observation: Researchers observe and record behaviors in daily life.
- Immersion: Long-term involvement in the field to gain a deeper understanding.

- Reflexivity: Researchers acknowledge and reflect on their own biases and influences.
- Contextualization: Data is analysed within its cultural, historical, and social context.

The techniques employed in ethnographic research are:

- Field Notes: Detailed, systematic recording of observations.
- Interviews: In-depth, semi-structured, or unstructured conversations.
- Focus Groups: Group discussions to gather diverse perspectives.
- Surveys: Questionnaires or surveys to collect quantitative data.
- Content Analysis: Analysis of texts, images, or artifacts.
- Network Analysis: Study of social relationships and structures.

Ethnographic Data Analysis entails:

- Coding: Identifying themes, patterns, and categories.
- Theme Analysis: Examining recurring themes and meanings.
- Narrative Analysis: Studying stories and storytelling practices.
- Discourse Analysis: Analysing language and communication patterns.

Overall, the Ethnographic Methods employed in this study can be summed up as follows:

- Case Study: In-depth examination of a single case.
- Comparative Study/benchmarking: Comparison of multiple cases.
- Ethnographic Mapping: Visual representation of cultural landscapes.
- Life History: In-depth study of an individual's life.

While technological advancements predominantly influence the commercialization of greener hydrogen energy innovation, the cost competitiveness necessary for effective adoption hinges on substantial public support. The development of hydrogen innovations may be disrupted or halted without a social license from the public (Scovell, 2022; Wüstenhagen, Wolsink, & Bürer, 2007).

In that respect, public fear regarding new energy technologies such as hydrogen fuelling stations, nuclear power, and carbon capture and storage (CCS) has historically impeded planned projects (Dütschke & Ramana, 2011). Hence, comprehending how the public perceives Hydrogen Energy Technologies (HETs) is crucial to stimulating cleaner energy transitions while fostering efficient industry standards and adoption. This aimed to discern societal perceptions on the potential use of hydrogen for household heating and cooking in Africa, particularly Zimbabwe.

The constructivist paradigm values pluralism and the social construction of reality and fosters collaboration between researchers and participants to understand actions taken by the latter (Baxter & Jack, 2008). Key Informant Interviews (KIIs) (see Table 1.2 in Chapter One) were utilised to establish challenges, opportunities, and the nature of electrolysers among organisations involved in hydrogen production, distribution, and use in Zimbabwe.

Key informant interviews are invaluable as they facilitate data collection from knowledgeable individuals who may offer broader perspectives on a research phenomenon or situation (Cossham & Johanson, 2019). Key Informant Interviews (KIIs) and focus group discussions complement survey results (Food and Agriculture Organization of the United Nations, 2018).

A survey questionnaire was employed to ascertain energy perceptions in rural Zimbabwe. The survey instrument is included in the Appendix A section of this thesis, and this aspect of the study was relevant in establishing the statistical potential for hydrogen energy use in the area. Key data collected through the baseline survey questionnaire was instrumental in determining villagers' expectations regarding energy, time invested in securing household energy, and primary energy sources utilised in their households, among other parameters discussed further in Chapter Six.

3.15. Case Study Design

This study adopted the Case Study Design. A research design is an action plan linking research questions to research conclusions (Chowdhury & Shil, 2021). The study focused on two cases situated in Zimbabwe: the first involving organisations engaged in hydrogen production, distribution, and use, and the second focusing on Mukaratigwa Village in Shurugwi District.

Case studies examine phenomena within their real-life contexts (Chowdhury & Shil, 2021; Cash, Stakovic & Storga, 2016). While these two cases targeted different participants at different societal levels, they could not be amalgamated due to their unique characteristics. The study aimed to advocate for the commercialisation of hydrogen as a product.

Interdisciplinary approaches dictate that innovative and social methodologies guide invention. In this context, scientific invention within the energy innovation domain plays a critical role as noted in Cash, Stakovic & Storga (2016) in applying innovative science and testing innovations. The question arises: what begins first? This thesis balanced social and technical or scientific research application through a multi-level, instrumental multi-case study illuminating broader understanding and insights (Ibid).

Overall, case studies address the "why" and "how" of the phenomena under study. Importantly, with case studies, it is impossible to manipulate participants' behaviors due to the research's natural setting. Thus, contextual conditions are crucial, with the physical boundaries of the phenomena typically being clear (Yin, 2014). This study related to Mukaratigwa Village, and organisations dealing with hydrogen within Zimbabwe were included.

3.16. Study Population, Sample And Sampling Procedure

Several participant groups were identified for inclusion in this research. Anticipated users of hydrogen gas and the electrolyser's target area were Mukaratigwa Village (Village A and Village B) within Shurugwi District, Midlands Province, Zimbabwe, as noted in Chapter 1. The village comprised 98 households, with all participating in the study. Another participant group consisted of key informant interview participants, mainly from organisations previously engaged in hydrogen production and use in Zimbabwe. The identified organizations included the Meteorological Services Department, Sable Chemicals, Zimbabwe Power Company (ZPC), Zimbabwe Phosphate Industries (ZIMPHOS), Chemplex Corporation, Windmill Zimbabwe, Unilever Zimbabwe, BOC Gases Zimbabwe, Olivine Industries, SIRDC, University of Zimbabwe, and Harare Institute of Technology. These organisations do not encompass those key informant interviewees who participated in the village case study.

The study population included key organisations in energy systems planning, development, generation, and distribution sectors. Households within the electrical energy distribution network, although lacking access or utilisation were included. Key organisations with investments in energy, non-governmental organisations (NGOs), and community-based organisations (CBOs), which work in communities with various utilisation, access, and distribution circumstances, participated in this study. Multiple data sources were employed to enhance data credibility (Chowdhury & Shil, 2021).

The researcher grew up in the village and maintained interactions within the community. This familiarity afforded access that external researchers might lack, enriching the ethnographic component of the study through lived experiences in the village. Additionally, the researcher held a political position as a member of parliament representing the constituency encompassing Mukaratigwa Village. This connection facilitated easy access to selected key informant interviewees.

However, researcher bias due to familiarity with Mukaratigwa Village and access to strategic national information required careful management during the research process. To mitigate this concern, the researcher employed pre-designed tools for data collection: the survey questionnaire and the key informant guide. Furthermore, assistance from a research assistant was enlisted to help older participants with literacy and visual challenges in completing the questionnaire. Audio recordings captured during seven key informant interviews and two focus group discussions enhanced data integrity. These tools diminished researcher bias by timely recording debriefing notes post-interviews. Such measures contributed to achieving a 100% participation and questionnaire return rate, though some responses contained incomplete data, adhering to the research principle of voluntary participation.

3.17. Study Sample

In terms of sampling, the study centered on the 98 participants from the households forming the village. One participant was designated from each household to participate in the survey forming a representative cluster. Cluster sampling was employed for this participant category, ensuring that individuals were purposefully selected to adequately represent the contextual realities within the bounded area of study.

Key informant interviewees were similarly selected purposively from organisations closely linked to the village community, including representatives from the Environmental Management Agency and the Zimbabwe Power Company. Community leaders such as the headman, also participated in these key informant interviews.

For organizations and individuals involved with hydrogen technology in Zimbabwe, purposive and snowball sampling techniques were employed. These organizations totalled twelve, with an individual user of hydrogen identified through snowballing for participation in the study. It should be noted that the organizations engaged in hydrogen within Zimbabwe are limited.

3.18. Sampling Procedure

Survey participants were sampled as a cluster. Each family designated one individual to represent their household in the study. The researcher secured clearance from the Ministry of Local Government and Public Works, specifically from the Midlands Provincial Office, to conduct the research.

Before participant engagement, the researcher’s team introduced themselves, explained the study's purpose, and requested consent for one individual from each household to complete the questionnaire. Participants representing organisations focused on hydrogen were recruited through snowballing techniques, allowing for some instances where more than one representative participated in key informant interviews, leading to informal focus group discussions (FGDs). The research also strictly adhered to the ethical guidelines of the Association of Social Anthropologists of the UK (ASA), ensuring compliance throughout the research process.

3.19. Research Methods

The research employed survey methods and key informant interviews (KIIs) to collect data. Additionally, transect walks were conducted in the village and among organisations involved with hydrogen, allowing for a comprehensive appreciation of the technologies utilised in hydrogen production, distribution, and use (Emerson, Fretz & Shaw, 2011).

3.20. Data Collection Instruments And Procedure

A survey questionnaire was utilised to gather data from households in Mukaratigwa Village. The questionnaire was developed, pre-tested for validity and reliability, and then fully deployed in the study area. The instrument underwent additional review during pre-testing by selected local community leaders involved in the energy sector, ensuring exposure to qualitative research methodologies. The semi-structured KIIs guide was also developed, pre-deployed for testing, and improved based on feedback. Those reviewing the questionnaire were not study participants, ensuring objectivity. Follow-up questions emerged during interviews to enhance study results.

3.21. Data Analysis And Presentation

Quantitative data collected through the survey questionnaire was analyzed using SPSS® Version 2020. Qualitative data from key informant interviews underwent thematic analysis. Secondary data regarding electrolyser brands available in the global market was also analyzed in SPSS Version 2020 and presented using tables, charts, and cluster mapping. Comprehensive data presentation occurred through tables, graphs, pie charts, and direct quotations where necessary.

3.22. Human Safety And Study Ethics

This safety case contributed to the costs associated with operationalising the electrolyser, which was key in assessing the feasibility of hydrogen production and use, in Zimbabwean households. Consequently, inspection of equipment and materials along with participant training for compliance was to be conducted and supported by Swansea University. Consistent compliance is expected since the designed, built, and deployed electrolyser should meet international standards, with a dedicated tank farm for liquefaction and storage of experimental materials to be further installed for the study. Additionally, honesty, objectivity, and confidentiality were prioritised throughout the research process.

3.22.1. Safety Case For Hydrogen Gas

According to Chapter 20:15 of the Environmental Management Act of Zimbabwe (Government of Zimbabwe, 2019), hazardous materials encompassing substances, whether liquid, solid, gas, or organisms may harm human health or the environment. Hazardous substances are characterised by varying effects, including explosive, flammable, corrosive, oxidizing, and toxic attributes. Despite their adverse effects, these substances cannot be eliminated due to their importance for human and economic development. Instead, usage is regulated through registration with relevant environmental management regulators, such as the Environmental Management Agency (EMA), facilitating easy monitoring to protect the public and the environment.

SI 57 of 2014 mandates the registration of gas dealers involved in production, transportation, storage, and retail. This legislation requires all gas dealers to undergo environmental impact assessments (EIA) before production commencement. Hydrogen, being flammable and stored in pressurized gas cylinders, is categorized under explosive and flammable substances according to Chapter 20:15 of Zimbabwean law. While compliance with Swansea University ethics and safety standards is crucial, adherence to relevant Zimbabwean laws remains paramount.

3.22.2. Hydrogen Gas Hazards

Hydrogen gas-related hazards encompass physiological, physical, and chemical aspects. Physiological hazards include frostbite and asphyxiation, while physical hazards may involve component failures or embrittlement. Chemical hazards particularly, include flammability and explosion risks. Hydrogen's primary hazards stem from its flammability when exposed to air. Safety can be ensured when plant designers, operators, and users are fully aware of hazards associated with hydrogen handling.

Many hydrogen-related hazards arise from its odourless, colourless, and tasteless characteristics, making leaks undetectable by the human senses (Rigden, 2003). These attributes have led to the development of leak detectors and hydrogen sensors to address potential escapes within industrial settings. The similarities between hydrogen and air as both are colourless, tasteless, and odourless underscore the need for specific detection instruments like hydrogen gas sensors (Rigas & Amyotte, 2013).

Exposure to hydrogen flames, radiant heat flux, or extremely low temperatures can result in physiological hazards, including injury or death. Asphyxiation occurs when there is air composition, deficient of oxygen at levels exceeding 18% hydrogen. Additionally, exposure to liquefied hydrogen can lead to hypothermia, particularly if body temperatures fall below 32 °C, diminishing brain function.

When addressing safety in Mukaratigwa Village, it should be noted that the nearest clinic is 5 km away, with public transport intermittently accessible. Hydrogen fires generally burn for a shorter duration when compared to other hydrocarbons (e.g., methane and gasoline). Liquid hydrogen is stored in double-walled, vacuum-jacketed, super-insulated containers to mitigate risks.

3.22.3. Hydrogen-Related Hazards and Safety Considerations

Hydrogen is a versatile fuel with immense potential, but it also presents significant hazards that must be managed effectively in industrial settings. Below are the primary hazards associated with hydrogen and safety considerations to mitigate these risks:

1. Overpressure Injuries

- ***Hazard:*** Rapid release of hydrogen gas can create high-pressure environments, leading to overpressure injuries for personnel.

- ***Mitigation****:* Utilise pressure relief valves and safety protocols during maintenance and emergencies to prevent overpressure situations.

2. Hydrogen Embrittlement

- ***Hazard****:* Hydrogen can diffuse into metals causing brittleness and loss of ductility that may lead to structural failure.
- ***Mitigation****:* Use materials resistant to hydrogen embrittlement (e.g., stainless steel, certain alloys) and implement regular inspections for signs of degradation.

3. Mechanical Property Deterioration

- ***Hazard****:* In addition to embrittlement, hydrogen exposure can affect the mechanical properties of materials, impacting their strength and durability.
- ***Mitigation****:* Implement rigorous testing and quality control during material selection and equipment fabrication.

4. Flammability and Explosion Risks

- ***Hazard****:* Hydrogen is highly flammable and can ignite in oxygen or air. Its flammability range is approximately **4% to 75%** by volume in air.
- ***Mitigation****:* Strictly control hydrogen concentrations in the air, ensure proper ventilation in storage and processing areas, and use explosion-proof equipment. Implement rigorous monitoring to detect leaks promptly.

5. Auto-ignition and Heat Exposure

- ***Hazard****:* Hydrogen can auto-ignite at temperatures above **500 °C**, and exposure to hot surfaces or flames can lead to dangerous reactions.
- ***Mitigation****:* Conduct thorough thermal management and control processes; ensure equipment is kept below ignition temperatures and properly insulated from high-heat sources.

6. Unexpected Pressure Release

- ***Hazard****:* Sudden pressure release can lead to explosions or fire hazards, especially in the presence of flammable gases.
- ***Mitigation****:* Implement robust safety systems, including automatic shut-off valves and monitoring systems that detect and respond to pressure anomalies.

Thus, while hydrogen can be a valuable resource for energy and industrial applications, it carries significant risks that require careful planning and management. Safety measures, continuous training, and adherence to safety protocols are critical to preventing accidents and ensuring a safe working environment. Regularly updated data and risk assessments are essential for maintaining a proactive safety culture.

Table 3.3: Industrial accident reports recorded in Norwood industries

Category	**Number of incidents**	**Total incidents %**
Undetected leaks	32	22
Hydrogen-oxygen off-gassing explosions	25	17
Popping and pressure vessel raptures	21	14
Inadequate inter-gas purging	12	8
Vent and exhaust system incidents	10	7
Hydrogen-chlorine incidents	10	7
Others	35	25
Total	**145**	**100**

Source: Zalosh and Short (1978).

The data presented in Table 3.4 shows a breakdown of industrial accidents recorded at Norwood Industries, indicating that undetected leaks were the most significant category, accounting for 22% of all incidents. Other notable incidents include hydrogen-oxygen off-gassing explosions and popping and pressure vessel ruptures, constituting 17% and 14% respectively. This underscores the importance of effective safety protocols to mitigate these risks in industrial settings.

3.22.4. Regulation Of Explosive And Flammable Gases In Zimbabwe

Legal regulations governing flammable gas storage and sales are documented under Statutory Instrument S.I. 57 of 2014, primarily concerning liquefied petroleum gas (LPG). The laws surrounding hydrogen handling in Zimbabwe require clarification; hence this project is categorized under flammable, pressurized, and explosive gases, aligned with S.I. 57 of 2014. These laws govern the transportation, handling, and storage of gases while clarifying dealership terms and conditions involving explosive gases.

For instance, Section 3 of this secondary law prohibits the sale, production, storage, and transportation of gases by unlicensed individuals or organisations, mandating certification and licensing for gas tank production and testing. EMA reserves the right to conduct random inspections to assure compliance.

In addition to safeguarding human safety during hydrogen production, storage, transportation, and use, EMA aims to protect the environment. This approach aligns with achieving sustainable development through SDG 7 while avoiding detrimental impacts on SDGs 13, 14, and 15. During the Millennium Goals era, EMA initiated SI 7 of 2007, mandating all projects listed under the EMA Act (Chap 20:27) to undergo EIA processes before commencing operations. The primary purpose of EIA is to inform decision-making processes by identifying potential significant environmental effects and risks associated with development proposals, striking a balance among planetary, social, and economic considerations (i.e. Planet, People & Profit).

3.22.5. Safety And The Hydrogen Plant Design

Safety remains a significant concern throughout hydrogen gas production processes. Characteristics associated with hydrogen, necessitate the implementation and maintenance of Integrated Health and Safety Quality (ISHEQ) management systems. Amyotte (2013) advances that inherent safety is a proactive measure for eliminating or reducing hazards without over-reliance on engineering safeguards. Kletz (2003) formulates principles that facilitate the application of safety measures in industries.

Four strategies underpin safer hydrogen operations: minimisation, substitution, moderation, and simplification. Moderation entails optimising production processes to maintain hazardous substances at lower pressures and temperatures. Consequently, the plant will be fitted with automated detection systems. In line with the EMA guidelines concerning hazardous substances, competent personnel should be appointed, particularly with a trained safety officer appointed. Proper first-aid kits and fire extinguishing materials must be readily available consistent with ISO 45001 and 14000 standards. Given hydrogen's density, the formation of hydrogen gas clouds remains rare (Malkov, 2007).

Hydrogen is differentiated from other hydrocarbons, requiring articulated safety strategies integrating both passive and active engineering controls within safety hierarchies. Hydrogen disperses quickly, providing safety margins compared to more dense fuels; however, its low ignition temperature and flammability demand added precautions.

Inherent safety is deemed the most effective approach to risk mitigation, supported by passive engineering controls, such as pressure relief valves, to avert explosions while maintaining a careful monitoring program. Here, employee training is paramount to ensure adequate safety protocols are followed, underscoring the need for comprehensive training regarding hydrogen handling procedures.

3.22.6. Safety Management Systems

A prevalent tool in gas production and industrial practices is management systems aligned with identified risks. This encompasses process safety, occupational health, and environmental safety, guided by ISO 14001, ISO 45001, and ISO 9000 standards. Management must develop robust safety management policies and risk assessment procedures to minimize hazards and ensure equipment and human health protection.

Effective management warrants top-tier support to initiate, invest in, train, and implement sound safety systems (Moonis et al., 2010). Common safety management features across all sectors include continuous improvement, policy development, and senior management support.

Essential processes involve planning (hazard identification, risk assessment, risk control), implementation and operation (responsibility assignment, training, emergency preparedness), checks and corrective actions (incident investigation, auditing), and management reviews. These requirements fall under the "Plan-Check-Do-Act" paradigm (Creedy, 2004).

Preventative measures organised as a safety pyramid highlight key issues leading to the majority of accidents, as illustrated in Figure 3.5 below.

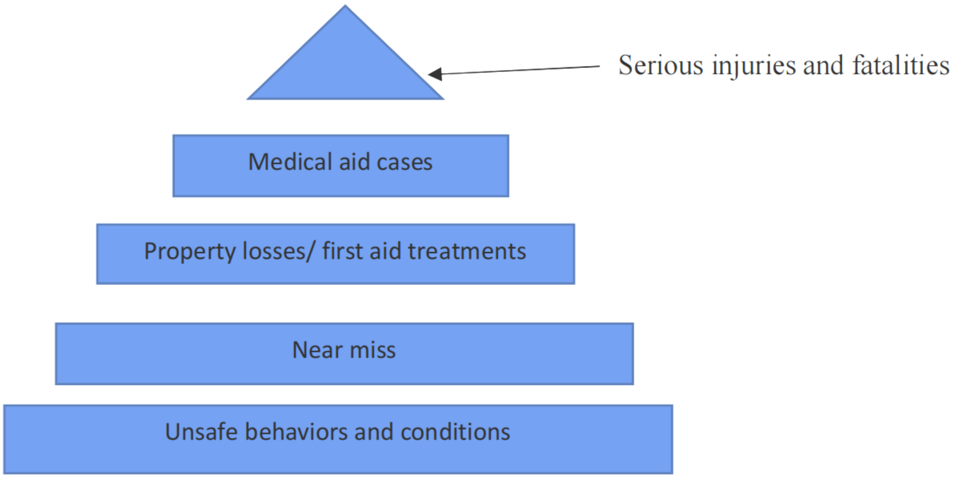


Figure 3.5: The Safety Pyramid (**Source:** Creedy, 2004).

Occupational and process safety are inseparable. ISO 45001 of 2018 calls for workforce safety, emphasising the need for safety representatives across sectors. This team is responsible for accident investigations and risk assessments. Process safety priorities emphasise intrinsic plant safety. Robust safety policies and designs lead to increased production and fewer hazardous incidents.

Safety management plans should delineate objectives and requirements encompassing work scope, organizational safety protocols, risk identification, equipment integrity, change management, ongoing safety reviews, and effective communication platforms. All stakeholders must be educated in health and safety, firefighting, and first-aid procedures for product stewardship. In discussing safety measures in hydrogen production, this study critically emphasises the importance of preventative strategies. As noted by Pasman and Rogas (2010), there is an urgent need to enhance focus on prevention and mitigation activities to ensure operational safety in hydrogen production plants. Sound and serviced firefighting equipment should be readily available, during the production, storage, and transportation of hydrogen gas.

Figure 3.6 below illustrates the systematic approach to risk assessment as outlined by Crowl and Jo (2002), which can be employed in hydrogen production facilities to identify and mitigate potential hazards.

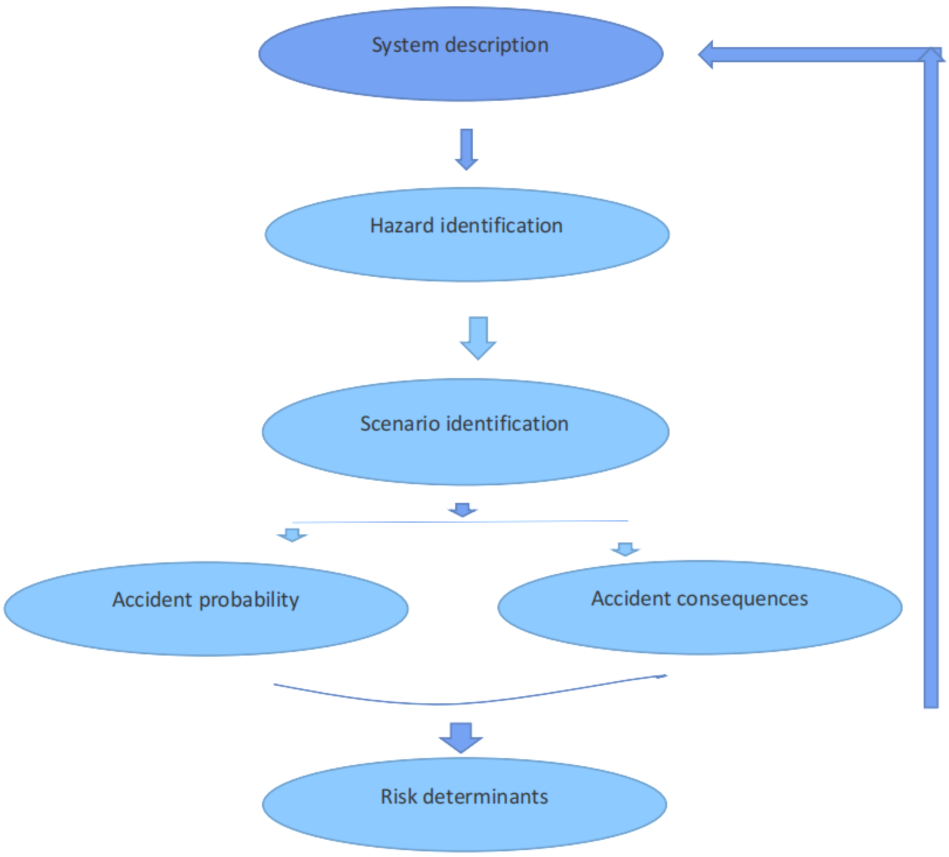


Figure 3.6: Risk assessment process (**Source:** Crowl and Jo, 2002).

3.22.7. Storage And Transportation Of Hydrogen Gas

Optimised storage options for hydrogen gas include compressed hydrogen in gas cylinders or tanks (GH_2), tethered balloon bags, low-pressure water displacement tanks (Low-pressure GH_2), liquid hydrogen (LH_2) in cryogenic tanks, and hydrogen adsorbed into metals to create metal hydrides (MH). Hydrogen is safest when stored in porous low-pressure tanks. The tanks are available at normal temperatures in a gaseous state either under medium (4.1 to 8.6 bar) or high pressure (140 to 400 bar) or in a liquid state under low temperatures and moderate pressure. At medium pressures, low-carbon steel or alternatives are used for storage; cold-rolled or cold-forged steels are not permitted due to embrittlement (Rigas & Amyotte, 2013).

Hydrogen can be stored as either gas or liquid. Gas storage typically involves high-pressure tanks (350–700 bar/5,000–10,000 psi). Liquid hydrogen storage mandates cryogenic temperatures, with hydrogen's boiling point at one atmospheric pressure being −252.8°C. A common strategy to avoid overheating a tank during refilling is gas pre-cooling. High pressure necessitates extremely robust tanks, employing materials such as carbon fibre and nylon-6 that are non-toxic and environmentally benign.

Though hydrogen's high-pressure characteristics present risks (Rivard et al., 2019), it is generally stored and transported in gas cylinders. According to BOC guidelines, hydrogen is deemed extremely hazardous. It requires storage in red cylinders under pressure. Hydrogen's lightness enables it to collect at the highest points of enclosed spaces unless adequately ventilated. Its ignition propensity and low energy requirements necessitate diligent safety precautions. The accompanying figure (Figure 3.7) exemplifies an onsite hydrogen storage tank within a plant setup.

Figure 3.7: Onsite hydrogen storage tank in a plant setup (**Source:** Author’s Compilation, 2024).

Transporting hydrogen gas cylinders requires competent dealers. While producers typically handle compressed gas transportation, consumers may utilize alternative methods. BOC guidelines stipulate strict regulations governing the transportation of empty and filled containers, including limits on cylinder quantities, prohibition of covering cylinders with canvasses, safe handling protocols, and clear labels. Mechanical lifters are recommended for gas cylinder handling, where feasible. Trolleys should be employed for cylinder transport and those working there should wear proper personal protective gear required. In emergencies, drivers transporting compressed gases are instructed to park far from other vehicles, minimizing risks.

3.22.8. Specific Hydrogen Gas Project Safety Case

This hydrogen project is designed to produce, store, distribute, and utilize hydrogen gas for domestic purposes, focusing on heating and cooking. The project aims to investigate hydrogen's potential as a cleaner energy source in Africa, particularly in rural Zimbabwe, where households predominantly rely on firewood exacerbating deforestation and biodiversity loss.

Hydrogen gas will initially be stored in butyl rubber bags before being transferred to gas cylinders for household appliance connections. Each gas cylinder has a full carrying capacity of 20 kg of hydrogen, which will be dispatched to participating households. Gas cylinders and butyl rubber bags represent the two secondary hydrogen storage solutions, maintained at average pressures of 500-700 as mandated by legal standards.

Throughout the project's lifecycle, the researcher will enforce effective safety, health, and quality management standards as outlined by ISO 14000, ISO 45001, and ISO 9001 management principles, as previously discussed. Implementing these management systems should bolster the overall performance of hydrogen production, storage, transportation, and usage by:

I. Enhancing the plant's ability to consistently provide products and services that meet customer and regulatory requirements;
II. Addressing project context and objectives associated with risks and opportunities;
III. Improving health and safety throughout the project's operational lifetime;
IV. Training all project members and support staff on safety, health, environmental, and quality management systems to achieve high standards of performance and risk mitigation;
V. Ensure continuous and proactive identification, elimination, and management of related project risks and opportunities, and;
VI. Promoting public awareness and capacity building for hydrogen gas users to mitigate associated risks.

This project framework established principles and processes to guide the daily management of project operations. The project must ensure that every participant bears collective and individual responsibility for realising project norms and expectations.

3.22.9. Project Health, Safety, And Environmental Issues

The researcher aimed to avoid and minimise risks to people, society, and the environment. The project's foremost priority is ensuring the health and safety of the study sample, the proximal community, and the research staff. Total adherence to health and safety standards should manifest in 100% compliance among all parties involved, whether directly or indirectly. The key objective of this project should be preventing all related accidents.

The foundational principles underpinning this project advocate that every individual and the operational environment must:

I. Provide a safe workspace for hydrogen production;
II. Maintain a marked and managed environment that ensures compliance with hydrogen production, storage, delivery, and usage protocols, and;
III. Foster an operational atmosphere emphasising awareness and adherence to safe practices when working with hydrogen gas.

3.22.10. Other Safety Aspects: H_2 Production, Storage And Use

All fuels inherently present some degree of danger. Safety measures should thus focus on preventing conditions where the three combustion components, namely the ignition source (spark or heat), oxidant (usually air), and the fuel (hydrogen) coexist. By thoroughly understanding hydrogen's properties, it becomes imperative to design a safe system incorporating appropriate engineering controls and guidelines to ensure safety throughout production, storage, handling, and usage.

Several hydrogen properties render its handling relatively safe compared to other fuels, including its non-toxic nature, allowing for operation at low concentrations. Being lighter than air, hydrogen dissipates rapidly upon release, further facilitating safety in case of leaks.

Other hydrogen characteristics, such as a wide flammable concentration range and lower ignition energy than gasoline necessitate additional engineering measures to enable safe use. Leak detection and proper ventilation are vital design aspects for secure hydrogen systems. Hydrogen flames are nearly invisible, and unique flame detectors are imperative for safety. Additionally, as some metals may embrittle upon hydrogen exposure, suitable materials are critical for maintaining safety. Participants and research staff must also receive training on safe hydrogen handling protocols. Regular testing for leaks and tank drops is crucial to ensure safe hydrogen production, storage, and dispensing practices.

3.22.11. Safety Around The Production Plant

The hydrogen plant area shall be double-fenced to restrict unauthorized access. The outer fence will be four meters out of the inner fence to enhance safety by keeping passersby at a distance from plant operations. Passersby may have diverse behaviours, such as smoking, that could ignite hydrogen fires. Proper signage, including warnings about explosive and flammable hazards, shall be placed along the fences to inform of potential dangers associated with hydrogen gas.

The inner fence, designed primarily for the work area, will only be accessible to trained, competent research personnel and authorized individuals. Operations including refilling and loading for gas transportation will occur within the inner fence, maintaining a distance of at least 5 meters from the production area.

All work areas will be distinctly marked by defined pathways, with appropriate safety signs throughout the hydrogen production zone. The plant will be safeguarded to restrict unauthorized individuals from accessing hydrogen production processes. Only approved personnel will have access during designated work hours and at any time. Zones exposed to hydrogen must be entirely free of alcohol and smoking, to minimize accident risks associated with impaired judgment.

Fires assembly points will be strategically identified and clearly labeled within the plant area. These areas will serve as locations for safety briefings at the beginning of each shift, involving both the research team and any authorized visitors. In times of emergence, personnel will convene at designated assembly points to coordinate and trigger an appropriate response.

Given that the study was conducted during the COVID-19 pandemic, considerations for adherence to infection prevention and control (IPC) measures were to be strictly enforced throughout the research timeline.

Figure 3.8 below shows a sketch of the plant design and related safety features proposed to protect the outside environment from the production plant.

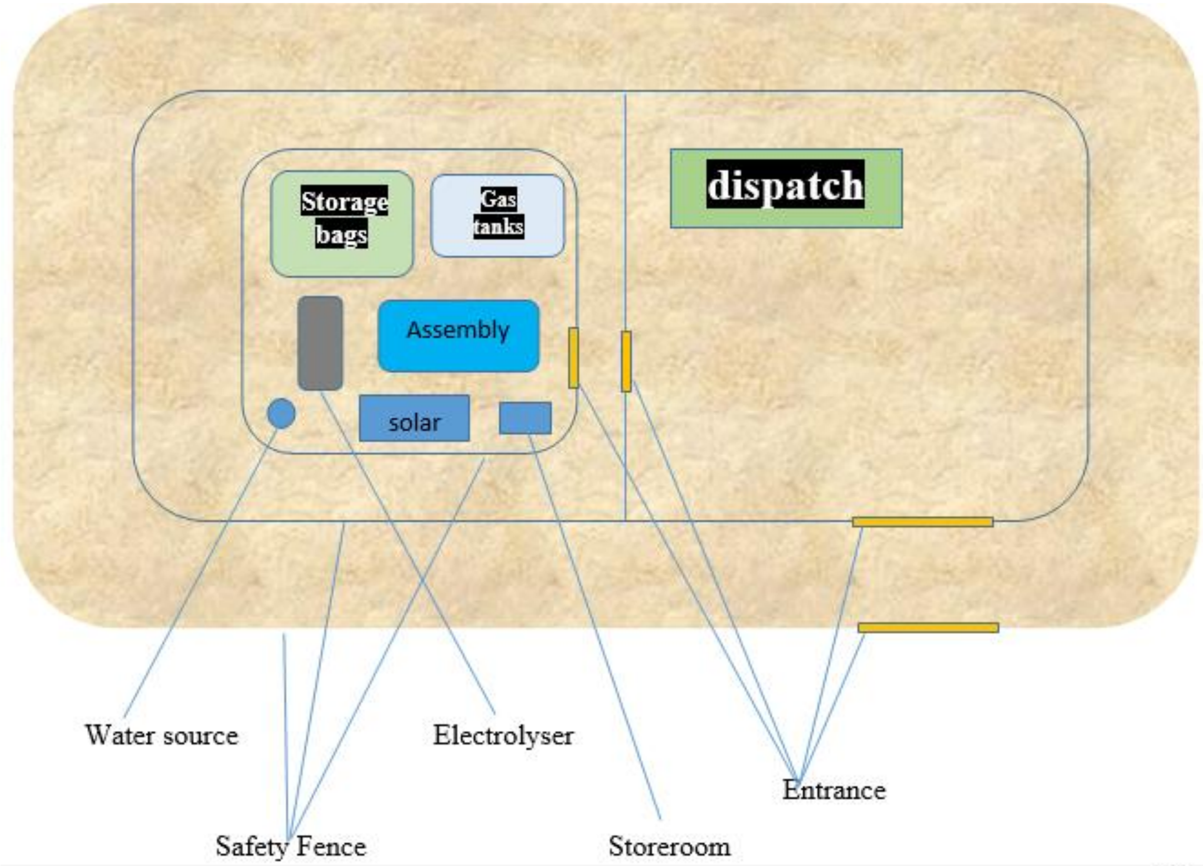


Figure 3.8: Sketch of Plant Design: Source (**Source:** Author’s Compilation, 2024).

The plant must be outfitted with hydrogen leak detectors throughout all connections—from the electrolyser to the butyl rubber bags and hydrogen tanks. Leak tests must occur every hour from the plant's commissioning and during operational activities, carried out by suitably qualified research personnel. Throughout the research duration and once community members begin managing the project autonomously, safety measures must continue to be enforced.

Additionally, the plant incorporates pressure gauges to aid in regulating hydrogen gas pressures in the butyl tanks and the cylinders. Emergency pressure release valves will be integrated into the design releasing pressure at a minimum of four meters above ground level to prevent risks to personnel and equipment as the gas disperses according to the Gaussian plume model.

Given the inherent fire risks associated with hydrogen production, firefighting and fire protection systems should be installed within the production plant. The plant will feature fire detectors to enable swift responses to fire hazards, recognizing that hydrogen flames remain nearly invisible during daylight, thus necessitating vigilant safeguards to protect lives and property. Two strategically positioned fire extinguishers must be available within and around the hydrogen production area, and temperature gauges will be placed in storage containers housing butyl bags to ensure safe storage conditions.

Temperature controls will maintain levels below 25 °C, mitigating gas expansion and explosion risks. Material safety data sheets should also be made accessible to the research team to promote safety and inform protocols in the event of hydrogen leaks, explosions, or other incidents.

or safety distances in hydrogen production and storage systems, the following guidelines and standards are commonly referenced:

3.22.12. Specific Safety Standard Guidelines

Adherence to safety standard guidelines for hydrogen is paramount. These are more important during the project implementation phase as the project has to be monitored for compliance with both International and British standards and Zimbabwean standards already noted above.

- International Organization for Standardization (ISO) 22734:2019 - Hydrogen generators using electrolysis.
- ISO/TS 18683:2016 - Hydrogen fuel - Storage and transportation.
- International Electrotechnical Commission (IEC) 62282-3-100:2019 - Fuel cell technologies - Part 3-100: Stationary fuel cell systems – Safety.

3.22.12.1. National Standards

- National Fire Protection Association (NFPA) 2:2020 - Hydrogen Technologies Code (USA).
- American Society of Mechanical Engineers (ASME) B31.12:2014 - Hydrogen Piping and Pipelines (USA).
- European Standard EN 12217:2012 - Gas infrastructure - Gas storage - Hydrogen storage.

3.22.12.2. Regulations

- US Department of Energy (DOE) Hydrogen Safety, Codes, and Standards.
- European Union's (EU) Directive 2014/94/EU on the deployment of alternative fuels infrastructure.
- Occupational Safety and Health Administration (OSHA) Guidelines for Hydrogen.

3.22.12.3. Industry Guidelines

- Hydrogen Industry Guide for Safety Distances (Hydrogen Europe).
- Hydrogen Storage and Handling Guideline (California Fuel Cell Partnership).
- Guidelines for Hydrogen Fuel Cell Vehicle Safety (SAE International).

3.22.12.4. Key Considerations

- Separation distances between hydrogen systems and nearby buildings, boundaries, or hazardous materials.
- Distance from ignition sources (e.g., open flames, electrical equipment).
- Ventilation and airflow to prevent hydrogen accumulation.
- Emergency response plans and training.
- Material compatibility and selection.
- Electrical and instrumentation safety.

3.22.12.5. Typical Safety Distances

- Hydrogen production: 10-30 meters (33-100 feet) from nearby buildings or boundaries.
- Hydrogen storage: 15-50 meters (49-164 feet) from nearby buildings or boundaries.

- Compressor or pump stations: 5-15 meters (16-49 feet) from nearby buildings or boundaries.

Please note that specific safety distances may vary depending on:

- System size and complexity.
- Location (urban, rural, or industrial).
- Local regulations and codes.
- Risk assessments and hazard analyses.

3.22.13. 40 Kw Electrolyser: Contextual Experiment Risk Areas

The use of electricity exposes individuals operating the electrolyser and the entire hydrogen production and handling system to fire hazards and burns arising from the hydrogen and electricity interfaces. The proximity of electrical systems to hydrogen poses the risk of explosion, impacting assets and any individuals who may access the vicinity.

Households designated for hydrogen use could be exposed to fire risks. These households consist mainly of children, women, and individuals with varying risk perceptions and understandings regarding hydrogen hazards. In rural communities, women frequently bear a significant caregiving burden, necessitating careful consideration of safety as they often interact directly with hydrogen technology for cooking and heating.

3.22.14. 40 Kw Electrolyser Scenario: Specific Key Safety Issues

Throughout the research process, precaution and risk-responsive measures were to be established to safeguard people and assets potentially exposed to hydrogen and the associated fire hazards from experimental operations, material outputs, and equipment. In response to concerns about the positioning of the solar array in relation to the electrolyser and the potential risk of hydrogen stratification and collection, careful attention has been given to the design and layout of the hydrogen production facility. The solar array will be oriented in such a way as to maximise exposure to sunlight while ensuring that any potential hydrogen released from the electrolyser can disperse safely.

To mitigate the risk of hydrogen accumulation, the canopies for the solar arrays will include ventilation mechanisms. Specifically, the design will incorporate open spaces or vents at the edges of the canopy to facilitate airflow, allowing any hydrogen that may escape during production to rise and disperse into the atmosphere rather than collect beneath the structure. Furthermore, compliance with safety standards mandates that the electrolyser be situated at a minimum distance from other structures, ensuring that any vented gases do not accumulate in enclosed areas. The area will be fenced and monitored regularly to ensure proper ventilation and minimize risks associated with potential hydrogen stratification.

All personnel involved with the project will receive training on hydrogen handling and emergency response measures. This training will cover the significance of proper ventilation and the identification of potential risk areas critical information especially relevant in instances where structures like canopies are involved (International Energy Agency, 2016). Through these integrated design choices and rigorous safety protocols, we aim to safeguard both personnel and surrounding assets from the inherent risks involved with hydrogen production. Collaboration with the district Environmental Management Agency (Zimbabwe) to ensure frequent independent site monitoring visits to reinforce compliance and maintain international hydrogen handling and utilization standards.

3.23. High-Level Plan

The high-level plan serves as a practical guide outlining the researcher's intentions throughout the processes, including receiving, installing, operationalising, and demobilising the electrolyser on the site.

I. The researcher had to initially receive comprehensive training on plant assembly, installation, operationalisation, and demobilisation from the supplier and Swansea University.

II. The Environmental Management Agency in Zimbabwe had to be engaged for site assessments to determine actual specifications and required production levels, including evaluations for project feasibility.

III. The researcher must ensure that the purchased electrolyser package includes conditions for installation, operationalisation, and demobilisation.

IV. Upon the electrolyser's arrival, the researcher will assemble it with assistance from a qualified engineer. At this stage, the electrolyser will remain non-harmful as it will not yet be connected to hydrogen production.

V. After assembly, the researcher will follow the recommended guidelines and reconfirm that all assembly processes meet the necessary standards set forth by the EMA, which will be invited to commission the plant alongside Swansea University.

VI. A high platform (4 meters) will be constructed for the solar panels, allowing for proper electrical configuration to minimize hazards from dangling cords.

VII. The double-fenced area will be erected using metal poles and meshed wire fencing before plant assembly. This setup guarantees the electrolyser is shielded from sunlight during installation.

VIII. Water tanks will be installed at a distance to promote efficient pumping into the plant, minimizing human intervention during processes to reduce potential risks.

IX. Hydrogen produced will be stored following prescribed conditions, utilizing a brick pillar structure and an iron roof, along with a cement slab floor.

X. A daily reporting procedure checklist will be established to ensure no aspects of the process are overlooked and to document all activities conducted within the plant area.

XI. Care will be taken to ensure the two participants designated for the experiment have properly constructed accommodations for hydrogen gas tank storage and burner usage.

XII. Training of the hydrogen plant operators and users will be conducted regarding safe hydrogen practices and burner operations, in alignment with guidelines from Swansea University and the Zimbabwe Environmental Agency.

XIII. The hydrogen plant and storage systems will remain locked except during monitoring by trained personnel.

3.24. Delimitation

This experimental phase of the study was meant to be situated within one ward (Ward 9) of Mukaratigwa Village in Shurugwi Rural District within Zimbabwe's Midlands Province. The study evaluated the potential for using hydrogen as an energy innovation and accessibility solution within developing countries, with a specific focus on Zimbabwe. Consequently, only Mukaratigwa Village (Areas A and B), alongside selected organizations and key informants, were involved in primary data collection. Published literature, grey literature, reports, and other sharable organizational information from participants were also compiled for this study. Methodologically, only survey questionnaires, semi-structured key informant interviews, unstructured observations, and document reviews were used to address the study questions.

3.25. Limitations

A primary limitation of this study pertained to funding constraints, which have hindered access to the actual electrolyser kit for experimentation. Mukaratigwa Village was the sole site designated for the overarching experimental research, while qualitative research participants were drawn from other areas to achieve balance between financial limitations and the study's objectives.

The study could not utilize the electrolyser since it focused primarily on assessing the feasibility of hydrogen as an energy vector for cooking and heating through quantitative and qualitative data, as proposed by Robbins (2007). The time required to procure, construct, and deploy the electrolyser for use within Mukaratigwa Village significantly extended the research timeline. To accommodate this limitation, the researcher utilised electrolyser design characteristics to engage with participants, acknowledging the absence of the physical electrolyser while incorporating participants experienced in utilizing hydrogen at an industrial level, alongside increasing the number of village participants. These approaches bolstered the study while equipping future researchers with insights derived from this research.

Due to the researcher's familiarity with Mukaratigwa Village, including potential biases stemming from access to strategic information, careful attention was adopted during the study. To mitigate possible bias, the researcher employed pre-designed tools for data collection: the survey questionnaire and key informant interview guide. Furthermore, assistance from a research assistant was utilised to aid older participants with literacy and visual challenges in completing the questionnaire. Audio recordings were made throughout the seven key informant interviews and two focus group discussions, ensuring a comprehensive data collection process. These tools proved beneficial in minimizing researcher biases, alongside the timely completion of debrief notes post-interview. As a result, the participation rate reached 100%, although some questionnaires contained incomplete data in accordance with voluntary participation research principles.

3.26. Justification, Policy Relevance, And Key Issues

Key poverty reduction models (Wisner et al., 1994 & 2003; Chambers & Cornwall, 1992) have often failed to achieve their intended objectives, although they have impacted numerous interventions (Nyandoro & Hatti, 2019). This perspective positions energy as possessing considerable potential to facilitate a genuine sustainable development-driven poverty alleviation in developing countries. Achievements in this regard necessitate innovative solutions that extend beyond immediate needs towards economic transitions, such as job creation, wealth generation, cleaner energy adoption, and women’s empowerment which are the key facets of sustainable development.

This study anticipated addressing women’s challenges and those of key disadvantaged populations, including the elderly, disabled individuals, girls, and terminally ill individuals. Therefore, the research challenged existing theoretical, practical, and policy frameworks. This multi-disciplinary approach (encompassing engineering and socio-economic development issues) is vital for tackling real-life challenges that require tangible solutions beyond mere theoretical advancements.

3.27. Chapter Summary

This chapter provided an overview of the methodology employed for this thesis. The primary objective was to elucidate how the research was conducted concerning research philosophy, design, and methods. The study sample and sampling procedures were discussed in detail. Notably, this research incorporated experimental and constructivist elements to address engineering aspects and social science methodologies, acknowledging that engineering innovations must be deployed in communities, ultimately contributing to national and human development. Sustainable development goals can thus be realised through ongoing technological improvement efforts to enhance human quality of life. Chapter Four further investigates different brands of electrolyser technologies globally, setting the stage for a deeper examination of national hydrogen production, storage, distribution, and use within Zimbabwe, which will be discussed in the next chapter.

CHAPTER FOUR

4.1. H_2 ELECTROLYSER DEVELOPMENT AND THE GLOBAL MARKET

Chapter Four provides an in-depth analysis of the global landscape of hydrogen electrolyser technologies, exploring various brands and their respective characteristics, applications, and market presence. This chapter emphasises a coherent narrative, clear objectives, and a structured framework for analysis. The chapter begins by categorising the most prevailing electrolyser technologies, namely Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), Solid Oxide, and Anion Exchange Membrane (AEM), and examines their market dynamics, performance parameters, and geographic distribution. This chapter addressed the objectives of this research, specifically those concerning the exploration of hydrogen as an alternative energy vector, the assessment of current energy resources in Zimbabwe, and the identification of challenges and opportunities for implementing hydrogen innovation. The discussion also highlights the trend of increasing global interest in hydrogen technologies, focusing on industrial-scale production and research advancements predominantly occurring in the Global North. By compiling quantitative and qualitative data related to market prices and energy consumption using a systematic literature review, this chapter facilitated a comprehensive comparative analysis of the various electrolyser brands identified, ultimately contributing to a better understanding of hydrogen's potential role within the Zimbabwean energy context and beyond. The chapter will culminate with a synthesis of insights regarding the environmental implications of hydrogen production in Africa and the necessary policy frameworks that could foster growth within this sector.

This chapter comprises a comparative analysis of the electrolyser market based on defined criteria: manufacturer, technological specialisation, geographic presence, operational capacity, and cost of the prevalent technologies, as well as various manufacturers' strategies and innovations. Manufacturers were evaluated based on their market presence, production capabilities, and strategic partnerships which influence their competitive dynamics in various regions, including North America, Europe, and Asia.

The Chapter was delimited to the study of manufacturers actively engaged in the hydrogen market with significant production volumes or demonstrated research capabilities. This delimitation allowed for a focused examination of market drivers, opportunities, and challenges for hydrogen technology development. Understanding the classification of these manufacturers facilitates a clearer picture of market dynamics, enabling stakeholders to adapt their strategies effectively within this rapidly evolving sector, particularly as developing nations, including Zimbabwe, seek to integrate hydrogen technologies into their energy systems.

4.2. Introduction

This chapter provides a comprehensive analysis of the global hydrogen electrolyser market, aimed at elucidating the current landscape, technological variations, and the commercial implications of these technologies. The primary goals of this chapter are threefold and rooted in this study's key objectives, particularly objective numbers (ii), (iii), and (iv), which are:

- To explore and categorise the various electrolyser technologies namely Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), Solid Oxide, and Anion Exchange Membrane (AEM).
- To assess market dynamics, including price variations, geographic distribution, and key players in the global market.
- To identify challenges and opportunities for the adoption of hydrogen technologies, particularly within the context of Zimbabwe's energy needs.

The chapter details the predominant electrolyser technologies and their market presence, highlighting the growing global interest in hydrogen as a viable alternative energy vector. A comparative analysis was then conducted, utilising quantitative data on market prices and energy consumption to reveal insights regarding the potential for hydrogen integration into Zimbabwe's energy system. The chapter concluded by evaluating the environmental implications and necessary policy frameworks to encourage growth in hydrogen production and utilization, particularly in Africa.

At the same time, it can be argued that evidence abounds to corroborate that hydrogen can play a complementary role to already existing renewable energy sources, as there is a growing trend of hydrogen electrolyser brands as well as ongoing research in several countries in the Global North. Insights that stand out in this chapter are that the electrolyser technologies are predominantly being developed in the Global North, with other regions and countries only acting as distributors, research collaborators, and users of the technologies, as is the case for Zimbabwe. This pattern has consequences for the adaptability of innovative solutions in Zimbabwe and other developing countries. To facilitate easy comparative analysis of the identified brands through a systematic literature review, identified electrolysers were first sized to a relatively common level. The data was then used for ascertaining the global market penetration levels of the various technologies and brands; and, of special note, more industrialised and industrialising countries have a higher uptake of hydrogen technologies although deindustrialising countries are experiencing a reduction in local use of hydrogen technologies as well as the hydrogen gas, in the industries.

4.3. Overview of Electrolyser Technologies

This section categorises and examines the primary technologies utilised in hydrogen production globally. The electrolysers are divided into four key types: Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM), Solid Oxide (SO), and Anion Exchange Membrane (AEM). Each technology's characteristics, advantages, and challenges are discussed in detail, with an emphasis on market dynamics, performance parameters, and geographic distribution. The four common technologies are as follows:

- ***Alkaline Water Electrolysis (AWE):*** *This* technology dominates the market due to its maturity and lower manufacturing costs. It is characterised by its relatively slow start-up time and susceptibility to corrosion. AWE technologies have been more established in countries such as Italy, the UK, and the USA, attracting significant industrial interest.
- ***Proton Exchange Membrane (PEM):*** Known for its efficiency and compact design, PEM technology is praised for producing high-purity hydrogen with a smaller carbon footprint. Despite high production costs, PEM systems are increasingly adopted in countries with robust hydrogen markets.
- ***Solid Oxide and Anion Exchange Membrane Technologies:*** These technologies are emerging, and represent a smaller market share. They are also currently undergoing R&D to enhance their commercial viability. Solid Oxide systems have not yet reached full commercial production, while AEM technologies show promise in scalability.
- ***Dominant Hydrogen Technologies Globally:*** *The* predominant technologies in the market are Alkaline Water Electrolysis-based and Proton Exchange Membrane electrolysis-based technologies (Pietra et al., 2021; Guo, Li, Zhou, and Liu, 2019).

The Anion Exchange Membrane-based technology comparatively had a lower uptake in the global market, while the Solid Oxide-based technology had the least uptake at the time of research. Reasons for the high and low uptake of these technologies are many. Alkaline Water Electrolysis is already embraced at the industrial level because its current density is about five times lesser than that required for the PEM electrolyser (Guo, Li, Zhou, and Liu, 2019). Conversely, PEM electrolysis has been largely embraced because it is viewed as the most efficient and practical technology for producing renewable hydrogen with high purity. Additionally, the electrolyser is simple and compact, with the potential for a small carbon footprint. It also minimises the extra cost of pressurisation since the hydrogen is delivered and used at high pressure (Ahmed, 2022; Guo, Li, Zhou, and Liu, 2019). Other reasons are that the alkaline water electrolysis hydrogen production technology is mature, and its manufacturing cost is low. However, its demerits are slow start-ups, corrosion, the complexity of the technology, frequent maintenance sessions throughout its lifetime, and the many components of the electrolyser itself (Pietra et al., 2021). Conversely PEM starts up faster, has no corrosion issues, is simple to maintain, and has fewer components. However, PEM's main challenges remain high manufacturing costs, which comparatively restrict its development as a hydrogen production technology (Guo, Li, Zhou, and Liu, 2019). Solid oxide electrolysers were still in their early stages of commercialisation and needed more work to be scaled up into commercial systems. The same applies to the Anion Exchange Membrane (Mayyas et al., 2022; IRENA, 2020). It is important to note that no single electrolyser technology performs better in all dimensions. There is, therefore, a need for continuous innovation and competition among manufacturers and innovators for the electrolysers to continue being improved. An improvement in one dimension often presents trade-offs in other areas (IRENA, 2020).

4.4. Hydrogen Electrolyser Market Segmentation Analysis

Hydrogen electrolysers are a crucial technology in the transition to a green hydrogen economy as they allow hydrogen production through water electrolysis and renewable energy. As the market for hydrogen electrolysers expands, segmentation analysis provides insight into how different factors may influence demand, growth potential, and competitive dynamics. Below is a comprehensive segmentation analysis for the hydrogen electrolyser market using a defined criterion:

1. Technology Type

- **Alkaline Water Electrolysis (AWE):**
    - An established technology with a significant market share.
    - Generally lower capital costs, but relatively lower efficiency compared to newer technologies.
    - Suitable for large-scale hydrogen production.
- **Proton Exchange Membrane (PEM) Electrolysis:**
    - Higher efficiency and better performance at varying loads than AWE.
    - Growing traction in applications with fluctuating renewable energy sources.
    - Higher operational costs due to the use of precious metals like platinum.
- **Anion Exchange Membrane (AEM) Electrolysis:**
    - A newer technology that combines the advantages of both AWE and PEM.
    - Potentially lower costs than PEM due to the absence of precious metals.

- **Solid Oxide Electrolysis Cells (SOEC):**
    - High efficiency, particularly when used in conjunction with high-temperature processes.
    - Still under development, with higher current cost implications but promising future potential.

2. Application

- **Industrial:**
    - Hydrogen production for chemical processes (ammonia synthesis, methanol production).
    - Use in refining and processing industries.
- **Transportation:**
    - Production of hydrogen fuel for fuel cell electric vehicles (FCEVs).
    - Infrastructure development for hydrogen refueling stations.
- **Power Generation:**
    - Hydrogen as a means of energy storage and grid balancing.
    - Direct use in gas turbines for electricity generation.
- **Other applications:**
    - Other applications are sectors such as food processing, electronics, and steel production.

3. Region

- **North America:**
    - Strong governmental support, particularly in the USA.
    - Investments in hydrogen and fuel cell technology driven by policy initiatives.
- **Europe:**
    - Leading region in hydrogen technology development and deployment.
    - The EU Green Deal and hydrogen strategies of individual countries promote growth.
- **Asia-Pacific:**
    - Rapid adoption in countries like Japan, South Korea, and China.

  - Investment in hydrogen infrastructure and partnerships for technology development.
- **Latin America:**
  - Emerging market with potential for green hydrogen production from renewable resources.
  - Investments in renewable energy could drive electrolyser adoption.
- **Middle East & Africa:**
  - Interest in hydrogen as part of diversifying energy portfolios; significant potential in hydrogen production leveraging abundant solar and wind resources.

4. End-User Industry

- **Chemicals Industry:**
  - Major demand for hydrogen in producing ammonia and other chemicals.
- **Energy Sector:**
  - Hydrogen production as an energy storage solution and its role in renewable energy integration.
- **Automotive Industry:**
  - Growing use of hydrogen in fuel cell technologies for vehicles.
- **Metals and Mining:**
  - Hydrogen is used in processes for steel production and to reduce carbon emissions.

5. Capacity

- **Small-Scale:**
  - Typically for on-site hydrogen production, targeting niche markets and distributed energy systems.
- **Medium-Scale:**
  - Suitable for local industrial applications and fuel production.
- **Large-Scale:**
  - Centralized hydrogen production facilities for large industrial applications and grid-level hydrogen storage.

4.5. Key Market Drivers and Challenges

Drivers:

- Increasing demand for clean hydrogen as part of global decarbonization efforts.
- Technological advancements are reducing costs and improving efficiency.
- Government policies and initiatives supporting hydrogen technology.

Challenges:

- High initial capital investment for electrolyser systems.
- Dependence on renewable energy availability to ensure economic viability.
- Competition from alternative hydrogen production methods, such as steam methane reforming (SMR) and biomass gasification.

The market segmentation analysis of hydrogen electrolysers highlights various contributing factors that influence growth, applications, and regional dynamics. Companies that operate in this sector should focus on emerging technologies and adapt to changing regulatory environments to capitalize on the growing hydrogen economy. Understanding these segments can aid stakeholders in tailoring strategies to position themselves effectively within this rapidly evolving market.

4.5.1. Global Market Dynamics

This section investigates the market presence of various hydrogen electrolyser brands, focusing on their geographic distribution and technological advancements. A detailed table (Table 4.1) provides an overview of the countries where these technologies are manufactured and their respective market penetration levels. Despite the prevalence of North American and European companies in hydrogen technology development, the analysis reveals that regions like Asia (specifically China, Japan, and Korea) are becoming increasingly relevant in global hydrogen markets. Several emerging manufacturers have been identified, including key players such as Ceres, Cockerill Jingli, Enapter, and Nel Hydrogen. This chapter thus, highlights their contributions, innovations, and strategic partnerships. By examining individual companies, the chapter illustrates how varied approaches to technology development can impact market dynamics.

Comparison of different electrolyser technologies and brands presented challenges due to proprietary information and varied operational parameters. Consequently, estimations and comparisons are made cautiously, providing insight into prevailing trends and market strategies.

4.5.2. Solid Oxide Electrolysis Cells (SOECs)

Global interest, with notable research and development initiatives, is mostly in Germany, the USA, and Switzerland. SOECs have gained attention for their high efficiency in hydrogen production, particularly when coupled with renewable energy sources (IRENA, 2020).

4.5.3. Expanded Geographic Coverage

This section considers countries that have recently invested heavily in hydrogen production and related technologies, such as:

- ***South Korea:*** Known for advancements in PEM and AEM technologies (Pietra et al., 2021).
- ***Netherlands:*** Recognized for integrating hydrogen technology with offshore wind projects (Godula-Jopek, 2015).
- ***Spain:*** Emerging as an important player in hydrogen production, especially for AWE and PEM technologies (IRENA, 2020).
- ***India:*** Increasing focus on electrolyser technology as part of a national hydrogen strategy (IRENA, 2020).
- ***Singapore and the United Arab Emirates:*** Both countries invested significantly in hydrogen technology development (Pietra et al., 2021).

4.6. Key Manufacturing Companies and Distributors

This thesis primarily dealt with the main technologies noted below:

- **AWE Manufacturers:**
  - Air Products (USA)
  - NEL ASA (Norway)
  - Siemens Energy (Germany) (IRENA, 2020).
- **PEM Manufacturers:**
  - Hydrogenics (Cummins) (Canada)
  - Ballard Power Systems (Canada)
  - ITM Power (UK) (Pietra et al., 2021).
- **AEM Manufacturers:**
  - Giner, Inc. (USA)

  - Elchemtech (Germany) (Godula-Jopek, 2015).

- **SOEC Manufacturers:**
  - Hysata (Australia)
  - H2U (Australia)
  - Siemens Energy (Germany) (IRENA, 2020).

4.7. New and Emerging Technologies

These technologies include emerging technologies or hybrid systems combining multiple approaches, such as innovative systems utilising SOEC and PEM components (Pietra et al., 2021).

4.8. Analysis of Market Trends

Analysis of the market trends provided insights such as increased investments in renewable energy, integration, and the emergence of hydrogen hubs in various regions, along with government policies supporting hydrogen technology deployment (IRENA, 2020). This section discussed how different technologies align with sustainability goals, carbon emissions reduction targets, and the circular economy, providing a more nuanced understanding of the technologies' potential on a global scale (Godula-Jopek, 2015). In that respect, Table 4.1 summarises some of the market trends below:

Table 4.1: Location of commercial hydrogen technology manufacturers for the global market

Technology Type	Location
Alkaline Water Electrolysis (AWE)	Italy, UK, France, USA, Germany, Canada, EU, Australia, Japan, China, Belgium, Denmark, Norway, South Korea, Netherlands, Spain, India.
Proton Exchange Membrane (PEM)	USA, Italy, Japan, France, Belgium, Canada, Denmark, Germany, UK, Norway, and South Korea.
Anion Exchange Membrane (AEM)	Italy, Germany, USA (notable R&D efforts)
Solid Oxide Electrolysis Cells (SOEC)	Denmark, Italy, Switzerland, Germany, Japan, Australia, and USA.

Source: Adapted from Pietra *et al*. (2021); IRENA, 2020 and Godula-Jopek (2015).

Table 4.1 reveals that the Alkaline Water Electrolysis fuel cell is manufactured in around 13 (44%) countries, while around 10 (33%) countries host companies that produce the Proton Exchange Membrane electrolyser. Only 6 (20%) countries host companies producing Solid Oxide-based fuel cells, while only one (3%) country hosts companies producing Anion Exchange Membrane electrolysers, as further presented in the pie chart provided underneath in Figure 4.1 below.

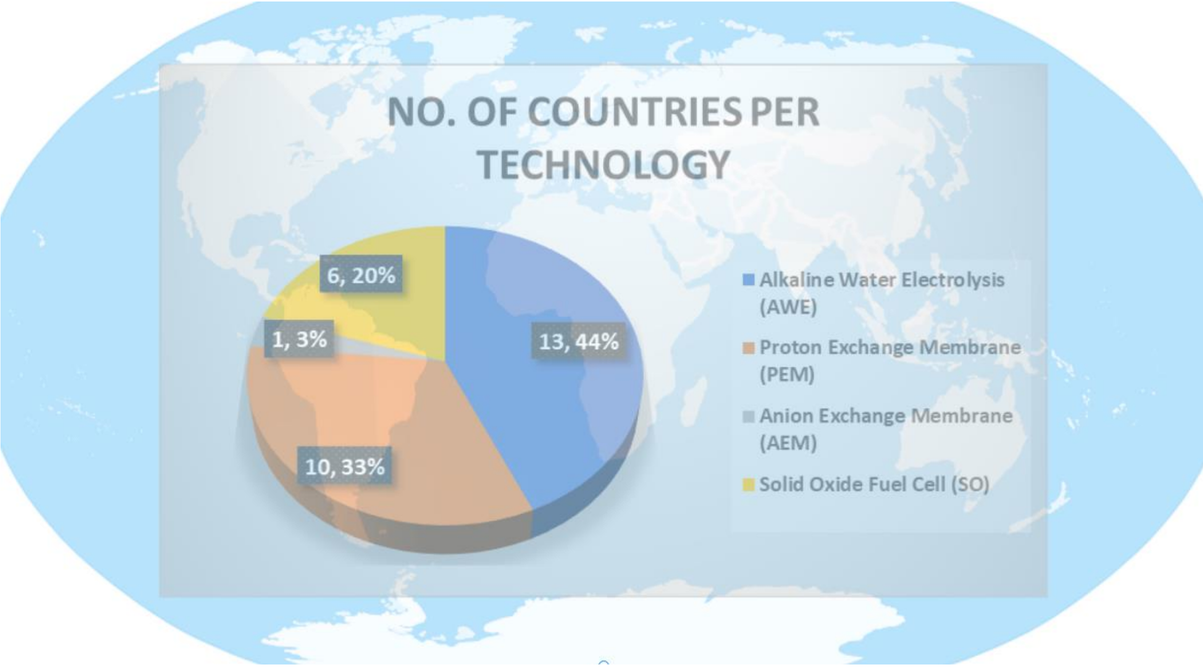


Figure 4.1: Pie-chart on the global distribution of hydrogen production technologies (**Source:** Author's Compilation, 2024).

It is important to note that among the countries presented above, Italy alone had been hosting companies working on commercialising all four technologies. Switzerland was involved exclusively in commercialisation of the Solid Oxide Fuel Cell technology. China only manufactures Alkaline Water Electrolysis electrolysers while the USA was more involved in commercializing Alkaline Water Electrolysis and PEM technologies. In addition, while these countries host different companies working on various technologies as indicated in Table 4.1 above, some companies operate in more than one country. Furthermore, some companies in other countries prefer investing in hydrogen projects implemented in foreign countries rather than their home territory. This is often due to limited physical land in particular countries that discourage using large tracts of land, due to the relatively small landmass, particularly in countries like Japan, where green hydrogen gas is supposed to be produced through solar-powered energy (IRENA, 2020).

The study acknowledges that the list provided in Appendix C is not exhaustive of global brands existing globally and the same view was also noted in IRENA (2020). A peculiarity remains that most of the identified brands or manufacturers of electrolysers are domiciled in countries situated in the North, with a lesser extent accounted for in Asian countries such as China, Japan, and Korea. There was no specifically targeted funding program for hydrogen technologies in China, although several manufacturers of large-scale alkaline electrolysers exist (Brown and Grunberg, 2022). Selected brands are further discussed below in this section of the study. Although more innovations were attributed to manufacturers based in Europe, patents are being filed in different countries, though they largely result from collaborations with companies in Europe and the USA. Patent families linked to hydrogen produced through water electrolysis have been increasing because water electrolysis is viewed as having better adaptability to various power sources, including solar and other renewable sources (European Patent Office (EPO) and IRENA, 2022; Reister et al., 2022; Davies et al., 2020). Research and development collaborations are thus key if the technologies are to be implemented urgently and meaningfully for household cooking and heating in Zimbabwe and locally in Mukaratigwa Village.

Prior analysing the electrolyser brands in the global market, it is imperative to acknowledge the impact of fossil fuel sources while emphasising the promotion of greenflation and its impacts. Production of hydrogen is not a new phenomenon globally, but the challenge is that 96% of hydrogen produced comes from fossil fuels, with electrolysis accounting for only 4%. Furthermore, 48% is from natural gas, 30% from liquid hydrocarbons, and 18% from coal. This implies a need to continue scaling up the production of green hydrogen. Consequently, the rise in research and development and the overall global transition to more sustainable cleaner technologies are paramount (Cetnar and Koped, 2009). Buttressing the ongoing discussion, hydrogen has been produced globally but largely not in a greener manner. China is advanced as the world's largest producer and consumer of hydrogen, accounting for 20% of global hydrogen demand. In the case of China, by 2020, 63.5% of its hydrogen supplies stemmed from coal gasification, which provided the largest national share. Other industrial processes, such as oil refining, contributed 21.2%, natural gas accounted for 13.8%, while electrolysis contributed merely 1.5% of the total hydrogen supplied in China (Zhou, Gosens, and Jotzo, 2022). Figure 4.2 below summarises data in Appendix D; which in particular is the disaggregated data on the uses of different technologies by various companies or brands.

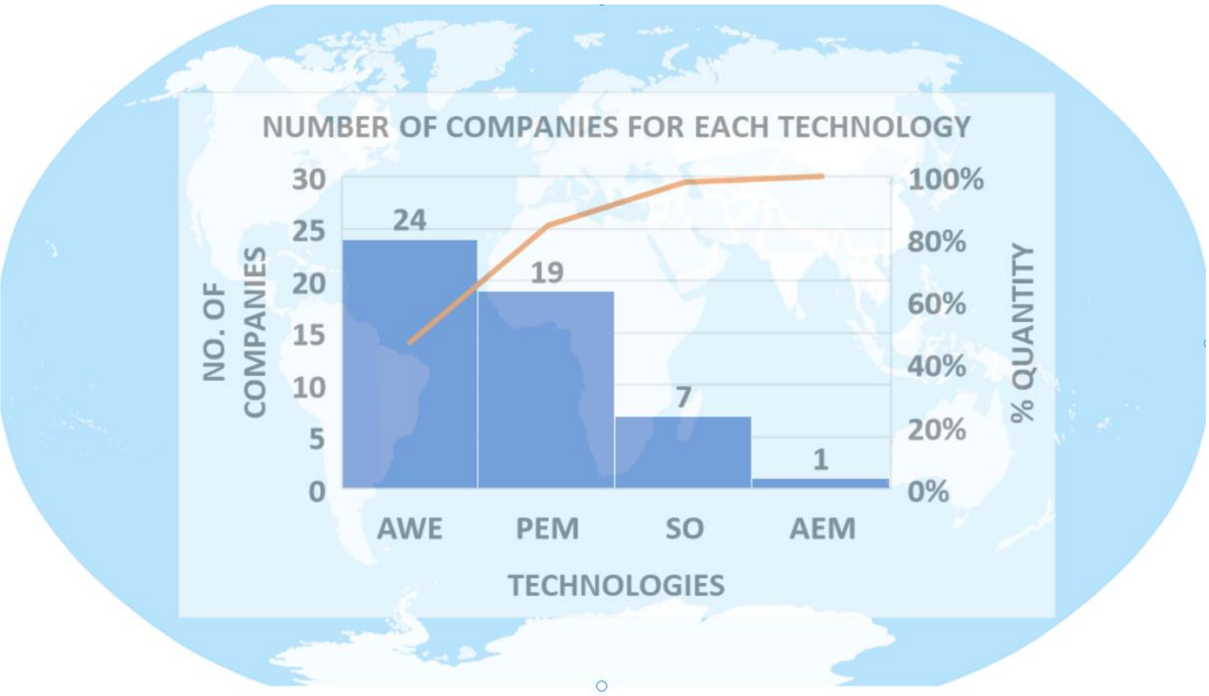


Figure 4.2: Number of companies involved in each technology (**Source:** Author's Compilation, 2024).

Figure 4.2 confirms that Alkaline Water Electrolysis and Proton Exchange Membrane technologies dominate as those being embraced for commercialisation globally. Solid Oxide and AEM had the least uptake. Among the companies analysed and presented in Appendix C as Figure 4.2, Solid Oxide is lowly adopted compared to AEM. This should be noted as primarily based on the list of selected companies or brands. In that respect, the claims by Pietra et al. (2021) and Guo, Li, Zhou, and Liu (2019) substantiated that Alkaline Water Electrolysis had the highest market penetration, followed by Proton Exchange Membrane, AEM, and then Solid Oxide.

4.9. Overview of Key Players in the Hydrogen Market

The hydrogen market is growingly populated by various companies, contributing to the development, production, and commercialisation of hydrogen technologies. Below is an expanded and detailed list of key players in this sector, highlighting their respective contributions and offerings:

4.9.1. Air Products and Chemicals, Inc.

- ***Overview:*** A global leader in hydrogen production, Air Products has been at the forefront of the hydrogen energy landscape for over 75 years.
- ***Offerings:*** The company offers various hydrogen production methods, including steam methane reforming (SMR) and electrolysis technologies. It also provides hydrogen fueling stations and was involved in projects that involved developing blue hydrogen (hydrogen produced from natural gas with carbon capture). Air Products is heavily invested in building hydrogen supply networks to support fuel cell vehicle infrastructure.

4.9.2. Ballard Power Systems

- ***Overview:*** A global leader in fuel cell technology, Ballard Power Systems focuses on clean mobility.
- ***Offerings:*** The company provides fuel cell products and technologies for transportation and stationary power generation applications. Ballard Power is committed to advancing hydrogen fuel solutions for buses, trucks, trains, and marine vessels, contributing to reducing carbon emissions.

4.9.3. BASF

- ***Overview:*** While mainly known as a chemical company, BASF plays a significant role in hydrogen production.
- ***Offerings:*** BASF is involved in hydrogen production largely through their Synthesis Gas production process, where hydrogen is a crucial product. They are researching sustainable hydrogen production methods, including using green ammonia in fertiliser production.

4.9.4. Ceres

Is largely headquartered in the UK, Japan, Korea, and China. It has been understood that brands such as Ceres have been licensing their technology to original equipment manufacturer (OEM) partners such as Bosch and Doosan to upscale production and achieve full-scale commercialisation. Such partners generate royalties for technology owners like Ceres. In this respect, Ceres has been focusing on fulfilling the needs and expectations of its licensees, regarding continuous operational improvement of equipment. In return, the innovators gain license fees and royalties in Pounds/kW sold. Ceres has produced green, blue, and grey hydrogen using fossil fuels and electrolysis. There was no mention of purple hydrogen produced by Ceres. Purple hydrogen is produced through thermochemical cycles or high-temperature steam electrolysis using nuclear energy (Zhou, Gosens, and Jotzo, 2022).

Ceres agreed with Shell to deliver a megawatt-scale solid oxide demonstrator by 2023 (Ceres, 2022). It should be understood that what Ceres and Shell are doing is common in many jurisdictions regarding producing both green hydrogen (which is hydrogen produced without carbon dioxide emissions) and blue hydrogen (where carbon dioxide produced is stored or reused), as well as grey, brown, and purple hydrogen (where carbon dioxide produced is released into the atmosphere). These hydrogen types are produced cognisant that many countries, including China, prioritise developing the hydrogen industry first, while greening is viewed as the second stage, after achieving the first step (Brown and Grunberg, 2022; Zhou, Gosens, and Jotzo, 2022).

4.9.5. Cockerill Jingli

This joint venture company was founded in 2018 by Suzhou Jingli Hydrogen Production Equipment Co. Ltd in China and the John Cockerill Group from Belgium. The company designs, develops, manufactures, and sells hydrogen production equipment across different industries. Headquartered in China, the John Cockerill Group has foundations that span over 200 years. The company conducts research and development and manufactures electrolysis hydrogen-producing equipment, and gas post-treatment equipment. Their electrolyser models and other products have been received in 30 countries worldwide as part of the company's brand internationalisation process. The expansion of the brands has resulted from international capital channeling toward hydrogen renewable energy research and development, contributing to China's new energy development strategy and its energy conservation and emission reduction strategy. This company further aims to support industrial integration services of hydrogen energy in line with international standards (John Cockerill, 2023). Cockerill Jingli is the second-largest company manufacturing electrolysers in China. Several European firms are partnering with Chinese firms such as Sinopec and Cummins due to China's potential for high sales and strength in the manufacturing industry (Brown and Grunberg, 2022; Zhou, Gosens, and Jotzo, 2022).

4.9.6. Enapter

It is important to note that most hydrogen electrolyser manufacturing start-up companies have been changing hands over time. Acta Italy was later renamed Heliocentrics Italy which is now Enapter listed on the London Stock Exchange in 2004. Acta turned to Alkaline Water Electrolysis technology development in 2007, particularly regarding electrolysers in 2010. The distributor of electrolysers for Acta has been Heliocentrics Energy Solutions. Countries showing interest in investing in Enapter have included Germany, Japan, and the United Arab Emirates, aside from Italy (H2 International, 2023), where it was originally founded. From the data presented in Appendix C, it can be deduced that most of these companies involved in original equipment manufacturing and the commercialisation of Solid Oxide and Anion Exchange Membrane technologies were still largely based in Europe, as confirmed in IRENA (2020) even though some offices were then found in Asia (2020) due to the large market the region presented. Enapter is also listed on the Frankfurt and Hamburg Stock Exchanges (H2 International, 2023).

4.9.7. Giner, Inc.

- ***Headquarters:*** Newton, Massachusetts, USA.
- ***Overview:*** Giner, Inc. is a research and development company specialising in advanced electrochemical technology, primarily focusing on fuel cells and electrolysers. Founded in 2001, Giner has been instrumental in developing systems that utilise hydrogen and other clean energy sources for various applications.

- **Offerings:**
  - *Proton Exchange Membrane (PEM) Fuel Cells:* Giner develops high-performance PEM fuel cells in transportation (such as buses and vehicles), portable power systems, and stationary power applications. Their fuel cells are designed to deliver high efficiency and reliability, enabling zero-emission solutions.
  - *Electrolysers:* Giner specialises in developing advanced electrolyser systems, particularly for green hydrogen production. Their electrolysers utilise renewable energy sources (like solar and wind) to split water into hydrogen and oxygen. Hydrogen and water contribute towards the development of a sustainable hydrogen economy.
  - *Research and Development Services:* Giner provides R&D services to government agencies and private companies, focusing on advancing fuel cell technologies and electrochemical systems. This includes collaborations on projects that aim at improving the efficiency, cost-effectiveness, and durability of hydrogen technologies.
  - *Hydrogen Production Systems:* The company has developed integrated systems that combine hydrogen electrolysers with renewable energy sources to create on-site hydrogen production capabilities, particularly for industrial applications, backup power, and vehicle fueling.
- ***Key Projects:*** Giner has been involved in several notable projects to enhance hydrogen technology, including partnerships with government entities and private sector companies to develop hydrogen production solutions for various sectors. Giner, Inc.'s commitment to innovation in hydrogen technologies makes it a significant player in the drive toward a hydrogen-powered future. It further reinforces the importance of advanced R&D in emerging energy solutions.

4.9.8. Green Hydrogen Systems

Founded in 2007 as a research and development company, Green Hydrogen Systems is based in Denmark. The company partners and customers include Siemens Gamesa, Nilsson Energy, Alliander, Lhyfe, Cleantech, Calvera Hydrogen, Nexeya, Orsted, Eurowind, H2FA, Wenger, Projects in the UK, and Lhyfe. Since 2017, the company has shifted into the commercialisation phase of its brand HyProvide. Green Hydrogen Systems further entered into a master supply agreement with GreenLab Skive to supply electrolysis hydrogen production plants. The company was also listed on the Nasdaq Copenhagen Stock Exchange in June 2021, receiving business orders from across the United Kingdom, Australia, Germany, Norway, and Chile since 2021 (Green Hydrogen Systems, 2023a; Green Hydrogen Systems, 2023b). It must be noted that the above companies can service the market through distributor networks or agents as part of an optimal partnership for exploration and exploitative learning and growth strategy (Vanhaverbeke, Duysters, Beerkens, and Gilsing, 2006). Zimbabwe can therefore take advantage of distributor opportunities to forge strategic partnerships for sustained innovation, although hostile relations between innovator countries and some developing countries remain a significant hindrance (Denhere and Moloi, 2022).

4.9.9. Hydron Energy

- ***Overview:*** A smaller yet innovative player, Hydron Energy focuses on developing green hydrogen solutions tailored for the African context.
- ***Offerings:*** This company provides projects developed to create decentralized hydrogen production stations that utilise local renewable energy sources to enhance energy independence in rural and peri-urban areas.

4.9.10. ITM Power

- ***Overview:*** ITM Power is a UK-based manufacturer of hydrogen energy systems, focusing on electrolyser technology.
- ***Offerings:*** The company specialises in PEM electrolysis, providing scalable hydrogen production solutions that can be deployed in various applications, including transportation and industrial processes. ITM Power also creates green hydrogen projects which pair electrolysers with renewable energy sources.

4.9.11. Kumatec (now under the new name Kyros H_2 Solutions GmbH)

Kumatec was founded in 1991 as a custom mechanical engineering company, initially working in automation and mechanical components. In 2009, Kumatec began exploring options to develop hydrogen solutions, and in 2011, it entered into a research venture with Forschungszentrum Jülich, one of Europe's biggest interdisciplinary research centers. In 2012, Kumatec received various funding, and in 2016, it won the Innovation Award Central Germany for its pressure electrolyser. The company got into a joint venture with KYOCERA AVX in 2018 and rebranded to Kyros Hydrogen Solutions GmbH in 2021, now headquartered in Föritztal, Germany (Kyros Hydrogen Solutions, 2022). Success through combined efforts between industry and universities or academia as demonstrated in this case, leads to new solutions while fostering the exploration of more mature technologies. The system builder, therefore, integrates exploitative-explorative learning that engenders continuous growth and expansion of technologies (Csedo, Zavarko, Vaszkun, and Koczkas, 2021).

4.9.12. Nel Hydrogen (Nel ASA)

- ***Overview:*** Based in Norway, Nel ASA specializes in hydrogen production technologies and has a strong commitment to green hydrogen solutions.

- ***Offerings:*** Nel provides modular electrolysers that utilize renewable electricity to produce hydrogen via water electrolysis. The company also offers hydrogen fueling stations and is involved in various pilot projects aimed at integrating hydrogen into industrial processes, such as producing ammonia and refining. Nel Hydrogen was founded in 1927 by Norsk Hydro and supplied both alkaline water electrolysers and efficient synthesis of Furfuryl Alcohol from corncob in a deep eutectic solvent system PEM electrolyser (Qin, Di, and He, 2022). Nel Hydrogen's largest hydrogen plant capacity was 135MW by the year 2019. The company has electrolysers in the USA, Bolivia, South Africa, Norway, Egypt, and Australia, among other countries. Illovo Sugar installed a Nel Hydrogen electrolyser A485 in 1983 in South Africa, with a hydrogen production capacity of 360 Nm^3/h. Over time, challenges with spare parts and other expertise support became evident due to sanctions that were imposed on South Africa. Nel Hydrogen was also listed on the Oslo Stock Exchange in 2014 (Nel, 2019). The electrolyser at Illovo Sugar was used for producing furfuryl alcohol, which is widely used in manufacturing resins, vitamin C, perfumes, lubricants, plasticizers, rubbers, fibers, lysine, dispersing agents, fuel additives, and biofuels, among other furan-based chemicals (Qin, Di, and He, 2022). Nel Hydrogen US is the former Proton Energy Systems Inc. and Proton OnSite, which was acquired in 2017. Nel Hydrogen US was founded in 1996 with the idea of applying PEM technologies for commercial hydrogen generation for both current and emerging industries and markets (Anderson, 2020). Notably, Proton Energy Systems has a HOGEN® generator capable of continuously producing hydrogen from renewable energy, grid power, and any mix of the two. It designs, develops, and manufactures Proton Exchange Membrane technologies and electrochemical products for hydrogen-generating devices and regenerative fuel cell systems that function as part of energy-generating and storage devices (Power Engineering, 2022).

4.9.13. Plug Power

- ***Overview:*** Plug Power focuses on alternative energy technology, primarily utilising hydrogen fuel cell solutions.

- ***Offerings:*** Their offerings include fuel cell systems for material handling, on-road vehicles, and hydrogen generation systems. Plug Power was also expanding its presence in the green hydrogen market, targeting renewable energy applications.

4.9.14. Pure Energy Centre

This company is involved in the designing, developing, and manufacturing of low- and high-pressure hydrogen electrolysers. The company boasts of being the first globally to install a completely off-grid community hydrogen electrolyser system connected to a wind turbine. The company started these projects in 2005 as a social entrepreneur. It further installed electrolysers in Asia, the Middle East, the Americas, and Europe. Pure Energy Centre has been engaged in hydrogen production, compression, and storage. The hydrogen electrolysers were mainly meant for housing, farmers, refineries, green transport, energy storage, gold and diamond mining, food processing, and power station cooling to achieve total green hydrogen use. The company produces small and large electrolysers, with the smallest electrolyser's production capacity being 0.5 Nm^3/h. The company also offers training on hydrogen and consultancy services in renewable energy, hydrogen technologies, oxygen, and nitrogen (Pure Energy Centre, 2021).

4.9.15. Sagim

Sagim manufactures and supplies hydrogen production units using electrolysis and chemical processes. The company also produces hydrogen electrolysers for national and international meteorological services supplying over 100 countries. With over 90 years of experience in manufacturing and supplying electrolysers, SAGIM is ISO 9001 and 14001 certified, and its headquarters is in France. The history of this company dates back to 1910, and throughout its life until it became SAGIM, it has collaborated with British, American, and Norwegian investors. SAGIM particularly has an alliance with Norsk Hydro Electrolysers AS (NEL Hydrogen). In 2001, SAGIM partnered with the American company Hydrogen Burner Technology, which uses the reforming process to produce hydrogen. In 2002, SAGIM, in association with NEL-Hydrogen, entered a new market, leading to the production of hydrogen generators. Bernard Cutillas held the majority of the shares in that company. SAGIM is also linked to the World Meteorological Organization (WMO) due to its hydrogen production plants for weather monitoring balloons. It is also a member of the Association of Hydro-Meteorological Equipment Industry (HMEI); the Prometeo, established in 1984, involved in meteorology, hydrogen, and the environment; the World Intellectual Property Organization (WIPO); and is part of NEL Hydrogen as previously noted (SAGIM, 2023).

4.9.16. Siemens Energy

- ***Overview:*** Siemens Energy is a global powerhouse in energy solutions that has increasingly focused on the hydrogen sector.
- ***Offerings:*** The company's offerings include proton exchange membrane electrolysis (PEM) technology, particularly suited for large-scale applications seeking to produce green hydrogen.

Siemens Energy's experience in renewable energy integration positions it well to support hydrogen production through solar and wind farms.

Siemens Energy has developed PEM electrolyser portfolios, starting in 2011 with a laboratory-scale demonstration. In 2015, it launched the world's largest power-to-gas plants using PEM electrolysers, and by 2018, the world's largest PEM cell was also constructed (Schnettler, 2021). In December 2022, Siemens, alongside other companies (ENGIE Solutions, Centrax, Arttic, and the German Aerospace Center (DLR)), and four universities in Europe—collectively known as the Hyflexpower consortium—announced the successful completion of the first stage of an innovative renewable energy project that began in 2020 (Yilmaz, 2020).

The project is located in Vienna and is claimed to be the first industrial facility globally to introduce an integrated hydrogen demonstrator. It demonstrates that green hydrogen can be produced on-site using an electrolyser. The hydrogen is then used for energy storage to co-fire an industrial-scale turbine that generates electricity. Trials are continuing into 2023, targeting a 100% hydrogen ratio. The technical feasibility of integrating green hydrogen into the existing energy infrastructure is central to this project. Existing energy infrastructure can be categorized into:

- Production infrastructure for both steam reforming and electrolysis
- Packaging infrastructure, which includes hydrogen compression, liquefaction, and physical/chemical packaging in hydrides
- Delivery infrastructure for hydrogen transport via road, pipeline, rail, and ship
- Onsite generation systems

Hydrogen transfer infrastructure utilised gravity to move energy from one location to another (Bossel and Eliasson, n.d.). The European Commission funded this project specifically through the EU's Horizon 2020 Framework Programme for Research and Innovation (Reillon, 2017).

The European Commission's 'Hydrogen Strategy for a Climate-Neutral Europe' report inspired this project, providing a foundation upon which the proof of concept was developed (Siemens Energy AG, 2022; Yilmaz, 2020). Siemens continued collaborations with universities, experts, and start-ups to progress its technologies (Siemens Energy, 2022). The developments at Siemens Energy underscore the importance of cooperation among government, business, and academia in advancing the hydrogen industry (Brown and Grunberg, 2022).

4.9.17. Sunfire

Established in 2010, Sunfire offered pressure alkaline and solid oxide electrolysers. Their electrolysers produced renewable hydrogen for decarbonizing industries, mobility, and energy. In the steel industry, hydrogen is used for iron application, blast furnace injection, and creating protective atmospheres. Refineries utilize hydrogen for desulphurization, hydrocracking, and hydrogenation; in the chemical industry, it is applied in ammonia production, hydrogenation, and isotope separation. In the mobility sector, hydrogen serves both road and rail needs, and, in the energy sector, it is used for industrial heating, space heating, and power balancing (Sunfire, 2022), as also noted in Riester et al. (2022). Sunfire partnered with research institutes and received financing through the European Union's Horizon 2020 for Research and Innovation (Reillon, 2017), Hydrogen Europe, and N.ERGHY (Sunfire, 2022).

4.9.18. Shanghai Zhizhen

Founded in 2016, this company is headquartered in the USA, UK, and China, and is backed by venture capital. It focused on the manufacturing and development of industrial fuel cell metal bipolar plates. Their offerings include design, configuration, ultrathin precision forming, high-speed laser welding, high-performance nano-coating, integrated sealing, and technology development for new energy applications, transportation, engineering, electrical generation, fixed power stations, communication base stations, backup power, and peak shaving. The company's products are utilised in fuel cells for ships, drones, backup power, and hydrogen energy storage, among other applications (Zhizhen New Energy Equipment, 2023). The cost of metal bipolar plates accounts for about 10%–15% of the total price of most high-power fuel cell engines, while coating those plates can represent about 50% of the total cost. The coating is crucial for the longevity of the metal bipolar plate (Energy Iceberg, 2022).

4.9.19. Toshiba

Toshiba Corporation's hydrogen business was registered in 2017 as Toshiba Energy Systems & Solutions Corporation. The business encompasses the entire spectrum from production and power-to-gas to hydrogen power storage and fuel cell technology development. It is profiled as being involved in the development, manufacture, and sales of energy business products, systems, and services (Yamane, 2019).

Moreover, the hydrogen supply chain business targets fuel, electricity co-generation, and the chemical industry utilizing electrolysis, PEM, and solid oxide technologies. These advancements were expected to accelerate the early commercialization of power-to-grid solutions for large-scale energy conversion, contributing to the realization of carbon neutrality (Toshiba, 2023; Osada, 2021).

4.9.20. Angstrom Advance

Based in Massachusetts, Angstrom Advance has been supplying hydrogen generators that rely on astronautic fuel cell technology to produce hydrogen by electrolysis of water that releases the produced oxygen into the atmosphere. Angstrom Advanced Inc. was founded in 2007 in Boston, USA. The company originated from a group of engineers who recognized the importance of research and development for the betterment of mankind. Starting with ellipsometers and the field of coated layers on PV cells, Angstrom has since expanded its offerings to include leading clean energy products (Angstrom Advanced Inc., 2023).

4.9.21. Asahi Kasei

Asahi commenced construction on an alkaline water electrolysis pilot plant for hydrogen production, with support from Japan's Green Innovation Fund and the New Energy and Industrial Technology Development Organization (NEDO). The company installed a 10MW alkaline water electrolysis system at the Fukushima Hydrogen Energy Research Field as part of this NEDO project, and many trials have been conducted since 2020 (Toshiba, 2020). Plans are underway to commercialize the system by 2025. Recognizing challenges in producing reliable products compatible with fluctuating renewable electricity, Asahi Kasei has introduced a pilot plant consisting of several electrolyser modules that perform trial operations responsive to power fluctuations, especially where wind and solar energy are used. These measures aim to achieve long-term durability and accelerate the development of its water electrolysis technology. Founded in 1920, Asahi Kasei is a diverse chemical manufacturer (Asahi Kasei, 2023).

4.9.22. ITM Linde Electrolysis (ILE) GmbH

- ***Overview:*** Linde Plc is a multinational industrial gas company with substantial investments in hydrogen technology.
- ***Offerings:*** Linde operates hydrogen production facilities globally, supplying hydrogen for various applications such as refining, chemical production, and emerging mobility markets. They also provide hydrogen fueling infrastructure for fuel cell electric vehicles and continually invest in developing low-carbon hydrogen solutions.

This joint venture between ITM Power and Linde Engineering was incorporated in 2020, focusing on delivering global green gas solutions at an industrial scale by leveraging ITM Power's PEM electrolyser technology and Linde's expertise in providing turnkey solutions related to gas production and processing, in addition to lifecycle support. The venture also offers related services and products, including hydrogen pressurization and liquefaction, buffering and storage systems, natural gas-grid injection, tube trailer filling stations, and hydrogen refueling stations, among others (ITM Linde Electrolysis, 2023).

4.9.23. Cummins

Cummins is working on building a new gigawatt Proton Exchange Membrane electrolyser manufacturing plant in Spain to expand the green hydrogen economy in Europe and globally. A site measuring 50,000 square meters has already been acquired for this purpose. This initiative aims to meet Cummins's carbon neutrality targets and sustainability goals. The plant is expected to be completed in 2023, with expansion of another factory in Belgium also projected. The company utilizes water electrolysis technology powered by renewable energy. Cummins has established several projects, including the world's largest PEM electrolyser in operation at 20MW in Canada; the first megawatt-scale demonstration plant for storing wind energy in the natural gas grid in Germany; the inaugural 100% hydrogen-powered passenger train fleet in Germany; and the first hydrogen refueling station for ships, cars, trucks, and industrial customers in Belgium (Cummins, 2023).

4.9.24. Hydrogenics (A Cummins Company)

- ***Overview:*** Originally an independent company, Hydrogenics is now part of Cummins Inc. and continues to innovate in the hydrogen sector.
- ***Offerings:*** Hydrogenics provides a range of products, including fuel cell systems and hydrogen generation solutions via electrolysis. Their equipment is utilised in renewable hydrogen production for transportation, power generation, and industrial applications, significantly contributing to the hydrogen economy.

4.9.25. De Nora

De Nora is undertaking a structured project to address the primary technological drawbacks of alkaline water electrolysis. With its partners, the company supplies anode and cathode coatings according to the electrolyser's operating conditions. In addition to electrodes, they supply other cell bipolar plates, anode or cathode separators (membrane or diaphragm), and gasketing systems that connect the separator and the cell frames. De Nora's research and development focuses on reducing manufacturing costs, minimizing technology risk, and improving stability, efficiency, and reactivity. The company also partners with reputable customers such as McPhy and Thyssenkrupp Nucera to realize the vision of green hydrogen (De Nora, 2023).

4.9.26. Elogen (Ex AREVA H_2 Gen)

Elogen focuses on PEM electrolysis solutions, supplying them to the Canadian firm Charbone for its green hydrogen projects in North America for an agreed period spanning from 2023 to 2026. Charbone is supervised by Elogen to ensure local manufacturing of PEM electrolysers and their components in both Canada and the USA (Pekic, 2022; Elogen, 2022).

4.9.27. ErreDue SpA

ErreDue designs, manufactures and markets solutions for on-site production as part of the commercialization process, blending and purifying hydrogen produced by electrolysis of water, nitrogen, and oxygen. The gases are used in various applications, including small, medium, and large-scale industrial sites, laboratories, and medical applications aligned with energy transition. The company produces high-purity hydrogen generators and systems for hydrogen, oxygen, nitrogen, and other complex gas mixtures (Morningstar, 2023).

ErreDue also manufactures mercury alkaline electrolysers that generate hydrogen and oxygen in two separate streams at the desired pressure. Research and development are central to the company's operations, and it was listed on Euronext Growth Milan in 2022 (Euronext, 2022). Their gases find applications in laser cutting, sheet metal heat treatment, welding, MAP packaging, enology, energy production, naval applications, and sintering. ErreDue collaborates with Saturn and NitroBox nitrogen generators and employs Pressure Swing Adsorption technology, hydrogen, and oxygen generators that utilize electrolysis, in addition to ErreDue's patented sodium borohydride/water reaction system (Metal Interface, 2022).

4.9.28. Hitachi Zosen

Hitachi Zosen became involved in hydrogen equipment development after securing funding through the Sunshine Project, which was announced in 1974 by the Ministry of International Trade and Industry's Agency of Industrial Science and Technology. In 1970, the company began developing a water electrolysis system, and in 1990, it initiated research on PEM-type water electrolysis systems. In 2000, it launched the PEM electrolysis system, HYDROSPRING®, and in 2004, demonstrated its ability to convert wind power into hydrogen. Since then, the group has developed hydrogen-generating systems that anticipate a growing hydrogen society.

Additionally, the company has researched and developed methanation processes that produce methane through chemical reactions between renewable hydrogen and carbon dioxide, thereby reducing reliance on fossil fuels. Other products include electro-chlorination systems that generate sodium hypochlorite via direct electrolysis of seawater or brine, which disinfects water and wastewater systems and prevents bio-fouling in power plants and other facilities. They also produce methanation equipment that generates methane by reacting renewable hydrogen with carbon dioxide. The Solid Oxide Fuel Cell is another product the company offers for directly converting chemical energy into electricity.

Hydrogen generation systems use water electrolysis powered by energy from photovoltaic systems and wind power through onsite equipment. The equipment is acclaimed for its high safety, convenience, efficiency, and adaptability to load variations. In 1881, Hitachi Zosen was established as Osaka Iron Works in 1934 before rebranding as Hitachi Zosen Corporation in 1943. The company originated in shipbuilding and has since expanded into the mechanical, chemical, and energy technology sectors, including green hydrogen, synthetic methane, and green ammonia (Hitachi Zosen Group, 2018).

Focusing on these companies and their offerings provides a comprehensive overview of the current hydrogen market landscape. Each player showcases unique hydrogen generation, storage, and utilisation approaches, thereby contributing to the overall hydrogen economy. Their innovations and technological developments support global clean energy transitions and highlight considerable opportunities for collaboration, investment, and growth within the hydrogen sector.

This comprehensive acknowledgment enhances the understanding of key players in the hydrogen market. It clarifies their contributions to the renewable energy landscape, emphasising the need for an in-depth exploration of company offerings.

4.10. H_2 Momentum: An Analysis of Global Progress and Coverage

The United States is one of the fastest-growing markets for alkaline hydrogen electrolysers worldwide. However, other countries are also developing hydrogen markets. Over the next decade, the U.S. market is projected to grow at a respectable rate of 21.4% due to government initiatives for expanding hydrogen production (Bloomberg, 2023). Proton On-Site is estimated to account for 17% of global total sales and is identified as the largest supplier among all hydrogen electrolyser manufacturers worldwide.

Five hydrogen supply corridors have emerged: North Africa and Southern Europe (Corridor A), Southwest Europe and North Africa (Corridor B), the North Sea (Corridor C, consisting of the UK, the Netherlands, Belgium, and Germany), Nordic and Baltic regions (Corridor D), and East and Southeast Europe (Corridor E) (Rossum et al., 2022).

Notably, Russia is rarely mentioned in the reviewed literature regarding the hydrogen supply chain, except in discussions of the Enapter brand. The country is not listed among manufacturers. The literature primarily highlights countries in the European Union and North America. Beyond the USA, primary participants in the International Energy Agency (IEA), the Technology Collaboration Programme on Alkaline Fuel Cells (AFC), and the Hydrogen Technology Collaboration Programs (TCPs) are investing heavily in hydrogen technology development (Rossum et al., 2022). The Hydrogen TCPs was established in 1977, while the AFC was introduced in 1990 (U.S. Department of Energy, 2020).

The AFC TCPs focus on multiple cell technologies across various applications and comprise 16 countries: Austria, Canada, China, Croatia, Denmark, France, Germany, Israel, Italy, Japan, Korea, Mexico, Spain, Sweden, Switzerland, and the United States. Croatia, Israel, Mexico, and Sweden were not identified as active hydrogen supply chain manufacturers in Appendix C, though the European Union is referred to broadly without specifying member states.

Thailand and Turkey were mentioned in Appendix C but are not noted as participants in the AFC TCPs or the Hydrogen TCPs. The Hydrogen TCPs also serve as a hub for international collaboration in hydrogen research, development, and analysis comprising 24 countries, the European Commission, and the United Nations Industrial Development Organization (UNIDO) as part of its membership and funding sources for most projects.

The 24 countries include Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Greece, Israel, Italy, Japan, Korea, Lithuania, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom, and the USA. Among Hydrogen TCPs members, Finland, Austria, Greece, Israel, Lithuania, Netherlands, Portugal, and New Zealand were excluded from the list of manufacturers provided in Appendix C (U.S. Department of Energy, 2020).

This pattern highlights the geopolitics of hydrogen energy, indicating that the Global North leads in innovation and usage of hydrogen energy technologies. It underscores distinct roles played by specific countries and regions in hydrogen innovation development, financing, technological incubation, commercialisation, production, distribution, and usage. Furthermore, successes in the Global North often stem from robust government support frameworks, which are crucial for long-term visibility and positive returns. Hydrogen innovation schemes are heterogeneous across regions and sectors while largely nonexistent in other parts of the globe. Consequently, countries vary in their actions and visibility within the broader hydrogen value chain (Gilles and Brzezicka, 2022).

The International Energy Agency has 30 member countries, primarily belonging to the Organisation for Economic Cooperation and Development (OECD), which has 37 member countries and five key partners. IEA associates include Brazil, China, India, Indonesia, Morocco, Singapore, South Africa, and Thailand (International Energy Agency, 2021). Table 4.2 below summarises the countries that are part of the IEA, ACF TCPs, Hydrogen TCPs, and the OECD.

Table 4.2: Countries in IEA, AFC TCPs, and Hydrogen TCPs

Category	Country	Total
IEA Members	Australia, Austria, Belgium, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Japan, Korea, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.	30
IEA Associates	Brazil, China, India, Indonesia, Morocco, Singapore, South Africa, Thailand.	8
AFC TCPs Members	Austria, Canada, China, Croatia, Denmark, France, Germany, Israel, Italy, Japan, Korea, Mexico, Spain, Sweden, Switzerland, United States.	16
Hydrogen TCPs Members	Australia, Austria, Belgium, Canada, China, Denmark, Finland, France, Germany, Greece, Israel, Italy, Japan, Korea, Lithuania, Netherlands, New Zealand, Norway, Portugal, Spain, Sweden, Switzerland, United Kingdom, United States of America.	24
OECD Members and Associates	Australia, Austria, Belgium, Canada, Chile, Colombia, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Israel, Italy, Japan, South Korea, Latvia, Lithuania, Luxembourg, Mexico, Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States + associates (Brazil, China, India, Indonesia, South Africa) + applicants (Argentina, Brazil, Bulgaria, Croatia, Peru, Romania; Costa Rica was invited to join).	42

Source: *Adapted from OECD (2021); Gilles and Brzezicka (2022).*

It can be deduced from Table 4.2 that most countries involved in the green hydrogen value chain are members of one or more organizations presented in this table. The OECD has programs across Africa, Eurasia, MENA, Latin America, the Caribbean, Southeast Asia, and Southeastern Europe, providing opportunities for innovations to achieve a global reach (OECD, 2021). Since Zimbabwe is not a member of the various bodies involved in hydrogen innovation and investment presented in Table 4.2, it may not receive funding opportunities from these countries unless it establishes mechanisms for collaboration. Moreover, Zimbabwe's frosty politico-economic relations with many countries in the European Union and those allied with the United States present additional challenges. To foster collaboration, especially regarding investments in hydrogen, Zimbabwe must continue building progressive relations with countries that have imposed sanctions (Matyszak, 2019).

The *"Zimbabwe is Open for Business"* mantra promoted by the New Dispensation presents an opportunity for engagement and re-engagement with these nations, as spearheaded by His Excellency, President of the Republic, Dr. E. D. Mnangagwa (Gruzd and Lalbahadur, 2020). Countries such as Great Britain, with the Commonwealth platform, serve as good launchpads for collaboration among member nations, including in research (Nyoni, 2019). Although these countries belong to different blocs, the number of countries in each bloc also varies, as illustrated in Figure 4.3 below.

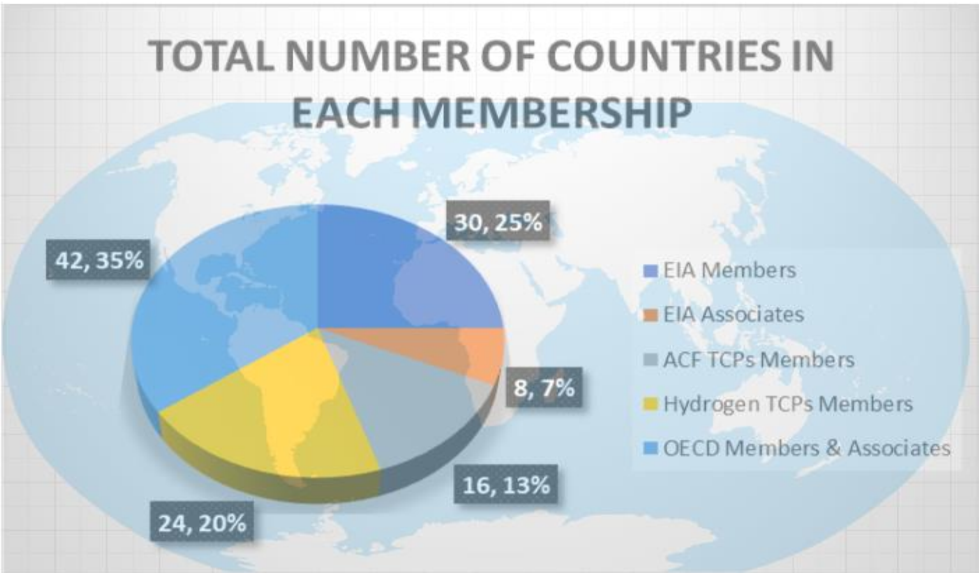


Figure 4.3: Total number of countries in each membership group (**Source:** Author's Compilation, 2024).

The OECD has the largest number of members, followed by the IEA membership and associates, Hydrogen TCPs members, while the AFC TCP has the fewest number of members.

4.11. Comparative Analysis of Electrolyser Brands

In this section, a comparative analysis of the identified brands showcases their pricing models and efficiency ratings (Figure 4.4). This analysis highlights varying costs associated with different electrolyser technologies and addresses the relationship between scale and efficiency, revealing a linear negative correlation between electrolyser size and efficiency. The analysis provides stakeholders, including policymakers and potential investors, with valuable insights into cost implications, manufacturing capabilities, and technological maturity necessary for informed decision-making regarding hydrogen adoption.

Comparing different electrolyser brands has proven challenging due to the novelty of some technologies and the secretive nature of costs, which are often classified information that companies use to maintain a competitive advantage. This lack of transparency hinders data access for third parties. Estimating costs is further complicated by the heterogeneity of parameters used to compare different technologies and brands (Patonia and Poudineh, 2022).

Notably, ISO 22734-1 pertains to hydrogen generators for industrial use. Generators produced in Europe must comply with safety regulations (2014/68/EU related to the construction and use of pressure equipment) and the "Atmosphere Explosibles" (ATEX) requirements (European Commission, 2001).

Considering the designed electrolyser for the targeted rural village is a 40kW size, Figure 4.4 below shows the general prices of various electrolysers on the market. These prices were largely sourced from suppliers in 2023 via email inquiries, while others were extracted from individual manufacturers' websites for generalization purposes in this study. A noticeable competition exists regarding hydrogen technologies, reflected by the many brands available in the market. Some brands are not sold off the shelf and are instead manufactured upon request; manufacturers typically require details about the intended electrolyser use before providing market prices for selected brand models.

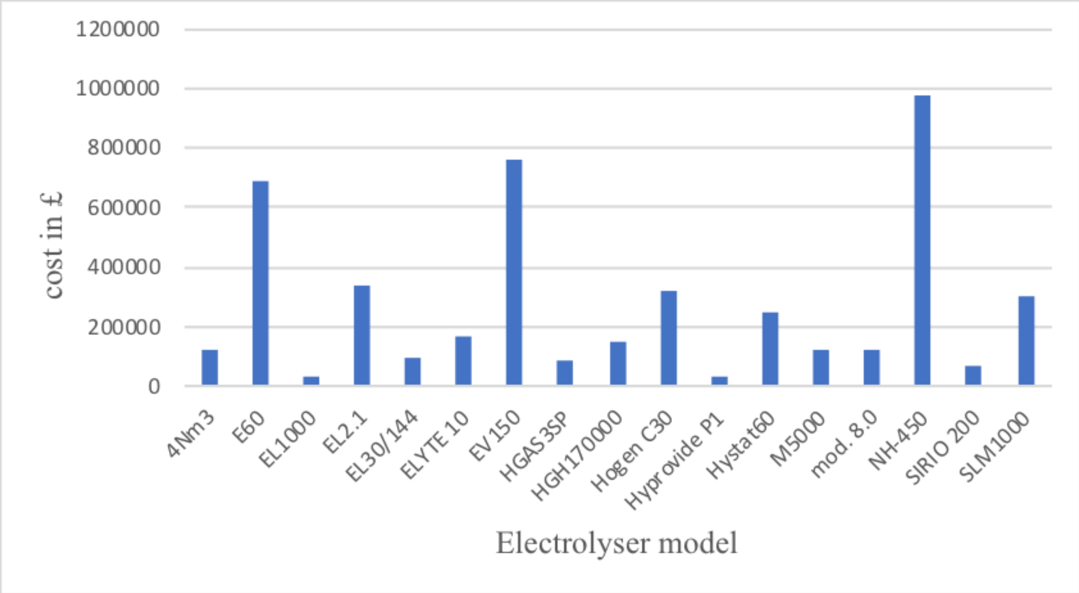


Figure 4.4: Prices of Electrolyser models in the global market (**Source:** Author's Compilation, 2024).

A 5kW electrolyser, for example, costs US$34,000 based on AEM technology, while its PEM counterpart is priced at US$35,000. Data for 10kW electrolysers shows a cost of US$72,000, also PEM based. Furthermore, 16 and 18kW electrolysers cost US$87,000 and US$98,000, respectively, both PEM based. A 20kW and a 25kW electrolyser are priced at US$120,000 and US$124,000, respectively, both also alkaline based. The 26.5kW electrolyser is priced at US$124,000, while the market price of the 30kW electrolyser was not provided by the researcher.

Market prices for 50kW electrolysers range between US$150,000 and US$165,000. While these prices are good indicators of the business case for electrolysers, it is essential to acknowledge that the reported efficiency levels are relatively low. The highest efficiency recorded was 74%, achieved by brands such as Acta and Elogen (ex AREVA H2 Gen). The presented data suggest that parameters related to hydrogen technology influence market acceptability and accessibility, along with the technology's usability and efficiency (Schone, Dumitrescu, and Heinz, 2023), which is pertinent to rural contexts in Zimbabwe.

Despite numerous countries producing hydrogen, only eight countries have established electrolyser brands globally: Italy, the USA, France, Denmark, Germany, the United Kingdom, Norway, and Canada (Figure x). Italy has the largest number of brands on the market (5), followed by the USA and France, with four brands each. The PEM brand, ELYT from France, boasts the highest efficiency of 82.4%, producing 0.88 kg/hr of hydrogen. However, a negative association (linear relationship) exists between the size of the electrolyser and its efficiency. Correlation analysis indicates a negative correlation between oxygen output in kg/hr and the efficiency of electrolysers ($p=0.04$, Pearson correlation= -0.574, Appendix D). This suggests that despite technological advancements in electrolyser design, manufacturers still face challenges in aligning efficiency with electrolyser size. The total pool of commercial electrolyser brands in the global market comprises three types: AEM, PEM, and alkaline, with a respective global distribution of 10%, 50%, and 40%. A detailed comparison of electrolyser brands in the global market can be found in Appendix C.

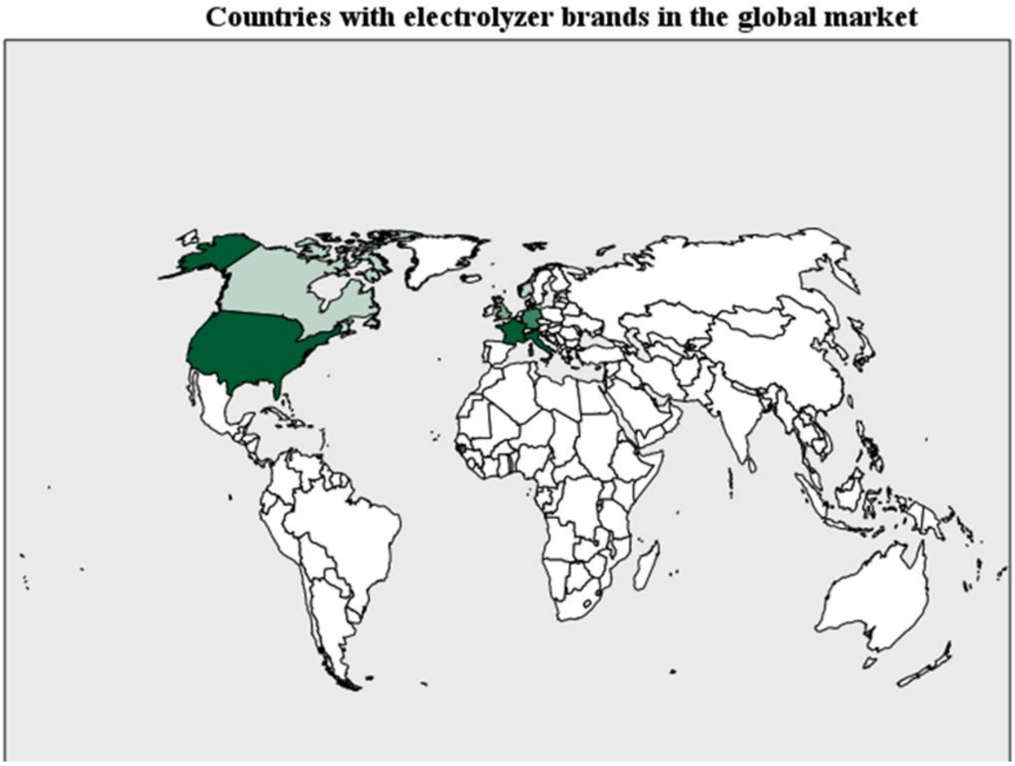


Figure 4.5: Original brand manufactures worldwide (**Source:** Author’s Compilation, 2024).

13.4 The Environmental Context of Hydrogen Production in Africa

This section explores the intersection of hydrogen production and environmental sustainability, discussing the role of green hydrogen in Africa's energy landscape. Although green hydrogen is primarily targeted for export to developed markets, it also presents local benefits and potential for sustainable development, emphasizing the importance of innovations that enable domestic hydrogen use, particularly for rural applications in Zimbabwe. The potential environmental triumph hinges on overcoming existing barriers to production and distribution, including the need for advanced infrastructure and financing mechanisms to support innovative hydrogen projects.

Green hydrogen produced in Africa is largely earmarked for global export. To achieve this, the developed world is funding green hydrogen production initiatives in Africa, recognizing the weather conditions favorable for solar energy generation intended for exporting to developed markets. Demand for hydrogen in the global market is anticipated to rise specifically in Europe, Japan, South Korea, and Southeast Asia (Brown and Grunberg, 2022). Southeast Asia is projected to account for 65% of the hydrogen market by 2050. In Southern Africa, Namibia and South Africa are identified as leaders in exporting hydrogen globally (Green Hydrogen Alliance, 2022).

It is essential to note that the African Green Hydrogen Alliance includes members such as Egypt, Kenya, Mauritania, Morocco, Namibia, and South Africa, focusing on public and regulatory policy, capacity building, financing, and certification needs to mobilize green hydrogen production for domestic use and export (Green Hydrogen Organization, 2023). The alliance aims to leverage potential exports to the EU, Japan, South Korea, and South Asian markets (Department of Science and Innovation, 2022; International Renewable Energy Agency, 2020). However, these countries continue to face common barriers to hydrogen production, including high transport costs, storage infrastructure requirements, and waste management challenges (Bossel and Eliasson, n.d.). This raises the critical question: Will green hydrogen production in Africa yield environmental benefits?

4.12. Policy Frameworks for Hydrogen Innovation

A transparent and conducive policy environment is vital for the successful development, implementation, and uptake of hydrogen technologies, fostering market acceptability and sustainability. A robust public policy framework surrounding hydrogen helps attract private financing and shifts long-term policy support from strict government interventions to mixed frameworks and eventually, market-based initiatives. Furthermore, high and widespread expectations for deployment unlock both public and private investment in sustainable infrastructure and manufacturing. The establishment of a multi-billion-dollar marketplace stimulates cost reductions through competition and innovation, while creating reliance among customers, investors, and suppliers on technology and each other, thus providing long-term stability (International Energy Agency, 2019).

This study posits that strong public policies can stimulate private investment and foster the infrastructure necessary for hydrogen production and distribution. The need for collaborative frameworks among governments, industry stakeholders, and research institutions is emphasized, showcasing examples from leading countries in hydrogen technology. The chapter proposes actionable recommendations for Zimbabwe to enhance its participation in the hydrogen economy through strategic partnerships and policy reforms aligned with global best practices.

Nevertheless, it is important to note that there is still insufficient policy activity globally to create hydrogen demand, critical in securing off-take agreements. Similarly, the lack of demand creation is viewed as a factor hindering final investment decisions (International Energy Agency, 2022). According to Shin (2022), an effective policy support roadmap should be established as groundwork for large-scale hydrogen utilisation in both national and global economies. An integrated policy approach is necessary to overcome initial resistance and ensure hydrogen reaches the minimum threshold for market penetration.

Four public policy pillars for hydrogen are proposed by the International Renewable Energy Agency (2020a): national implementation strategy, policy priorities, guarantees of hydrogen origin, and enabling government systems and policy actions. Such commitments from the government should assist the private sector in unlocking the capital needed to transition to green hydrogen (International Renewable Energy Agency, 2020a; Department of Science and Innovation, 2022). Numerous countries have shown interest in developing policy frameworks that foster hydrogen-related innovations, including China, France, Germany, Finland, Australia, Portugal, Norway, Spain, Japan, Chile, and the European Union (Patel, 2021). A discussion on green hydrogen policy frameworks, including those applicable to Zimbabwe, can be found in the following chapter.

4.12.1. Effects of Competing Hydrogen Technologies on Adoption

The competition among various hydrogen production technologies has significantly impacted the broader adoption of hydrogen as a clean energy source.

4.12.2. Diversification of Options

Multiple hydrogen production methods—such as steam methane reforming (SMR), electrolysis (including AWE, PEM, AEM, and SOEC), and biomass gasification—provide stakeholders with diverse options tailored to specific needs and conditions. This diversity can accelerate the overall adoption of hydrogen, as different end-users can choose the most efficient technology based on factors, such as cost, application, and local energy resources.

4.12.3. Market Innovation and Development

Competition drives innovation, producing ongoing advancements in efficiency, cost-effectiveness, and scalability. As technologies improve, they become more economically feasible, attracting investment and encouraging market entry by various players, facilitating wider hydrogen technology adoption. Figure 4.6 below shows a scenario of projected potential global routes and costs of hydrogen delivery from different producing countries to the European market. This scenario emanates from the realisation that the European Community is set to reduce GHG emissions by 55% by 2050. Hence, the community would need supplies from various regions with the potential to produce green hydrogen.

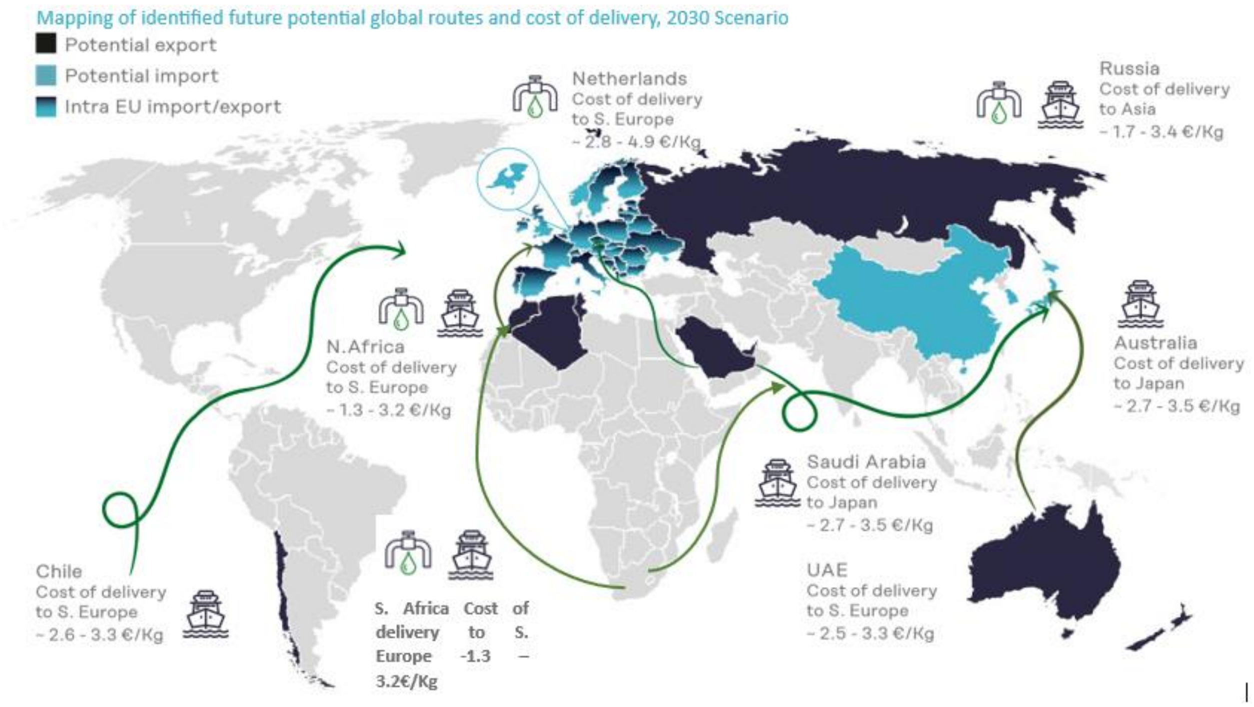


Figure 4.6: A 2030 Scenario of Future potential routes and cost of delivery (**Source:** Adapted from Corbetti et al., 2024).

4.12.4. Tailored Solutions for Local Conditions

Different geographical regions possess varying resources (e.g., renewable energy potential), regulatory frameworks, and market demands. Competing technologies allow for tailored solutions; for example, countries with abundant natural gas may prioritise SMR, while those rich in renewable energy may focus on electrolysis projects, fostering adoption in diverse contexts. Different types of hydrogen technologies are expected to continue to grow on the market and their competitiveness will have an impact on the level of market uptake globally. Figure 4.7 underneath presents a 2030 scenario of potential hydrogen prices by source.

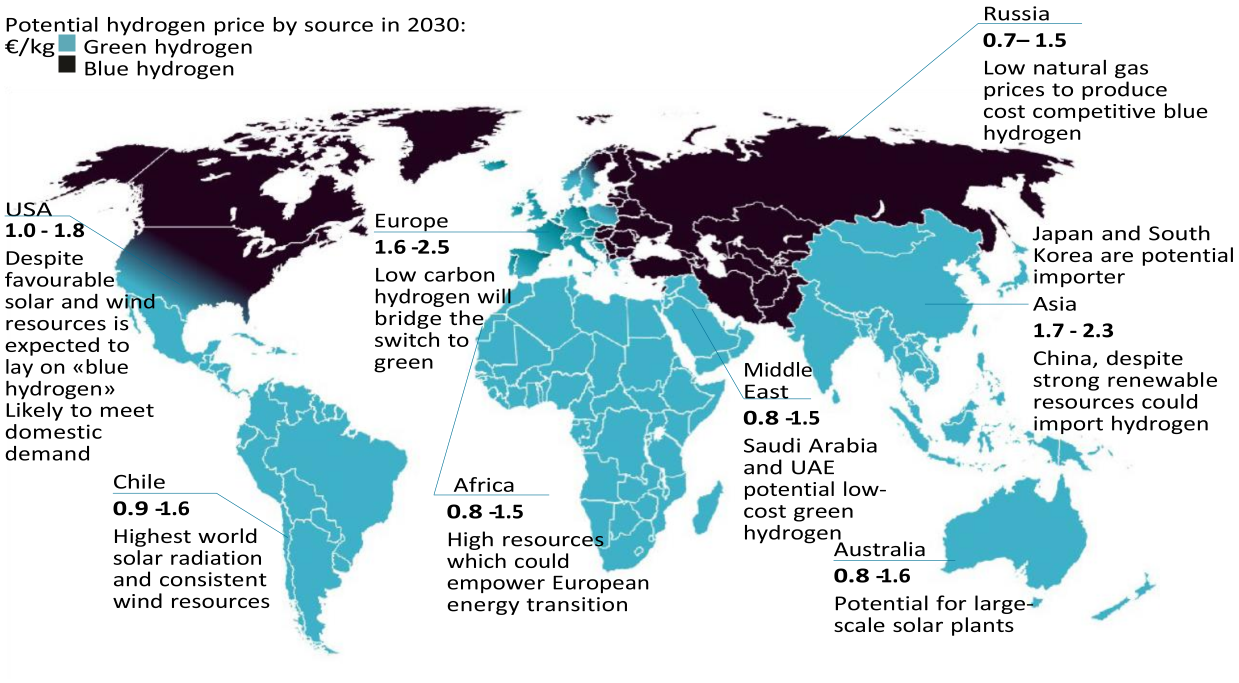


Figure 4.7: 2030 scenario of potential hydrogen prices by source (**Source:** Adapted from Corbetti et al., 2024)

4.12.5. Regulatory and Policy Effects

Multiple technologies often attract different government incentives and support frameworks, leading to uneven development across technologies and regions. When policies favor specific technologies, it fosters their adoption. However, this can create a fragmented market, wherein stakeholders may prioritise short-term benefits over long-term strategic investments.

4.12.6. Reasons Dominant Technology Has Not Emerged

Several factors explain why completely dominant technologies have not yet emerged:

4.12.7. Technological Maturity Levels

Different hydrogen production technologies are at various maturity stages. SMR is currently the most established method and boasts extensive existing infrastructure. Conversely, electrolysis technologies, while advanced in laboratory settings, may still struggle with scalability, market costs, and efficiency.

4.13. Market Preferences and Applications

Various market segments have unique requirements that may be best met by different technologies. Industries may prioritise diverse factors such as purity, cost, renewable integration, and carbon footprint. This divergence in priorities indicates that no single technology can universally meet the needs across all sectors.

4.14. Economic Considerations

The economics of hydrogen production are influenced heavily by local energy resource availability, applicable regulations, and technological investments. Factors such as energy costs, capital investments, and operational expenditures vary widely, complicating the emergence of a single dominant technology across diverse economies.

4.15. Transition and Hybrid Solutions

The transition to hydrogen is complex, and stakeholders often seek hybrid solutions that utilize multiple methods, capitalizing on the strengths of various technologies. This trend contributes to the absence of a single dominant technology, as companies frequently adopt a mix of methods to meet operational needs and sustainability goals.

4.16. Investment and Policy Dynamics

Fluctuations in investment and policy support for different technologies can lead to uneven development. If government policies or economic incentives shift toward one technology, other viable technologies may miss the necessary attention for growth, resulting in a fragmented market landscape.

In conclusion, competition among hydrogen production technologies plays a crucial role in shaping the market landscape and promoting adoption. While this diversity presents opportunities for innovation and tailored solutions, it also contributes to the complexity and fragmentation of the hydrogen market, making it challenging for a single technology to emerge as dominant. As the hydrogen economy evolves, continued advancements, supportive policies, and changing market needs will inform the eventual landscape of hydrogen technologies and their adoption rates.

4.17. Chapter Summary

This chapter contextualised the development and commercialisation of hydrogen electrolyser technologies within the global market, emphasising their implications for Zimbabwe and Africa. The analysis indicates that while progress in hydrogen innovation is robust globally, significant barriers remain for developing countries to gain comprehensive access to these technologies. The findings underscore the urgent need for tailored policy action, research and development investments, and international collaboration to harness hydrogen's potential for sustainable energy solutions in Zimbabwe and beyond.

The study revealed many hydrogen brands or companies utilising different models and technologies. The penetration of hydrogen technologies in Africa remains low, and the continent continues to rely on imported hydrogen equipment, putting it at risk whenever suppliers can no longer deliver, largely due to international politics. The existing electrolysers are still costly for small-scale use, although there is significant demand potential for hydrogen on the continent. Trends in the broader market also point to ongoing innovations being scaled up for commercialisation; some innovators are selling their discoveries to the market for further development. Large-scale companies are particularly interested in technologies with established proof of concept, readily acquiring or partnering with innovators or patent owners, while some brand owners choose to lease their technologies. Many brands exist, and there is still significant work ahead to ensure that hydrogen remains green. Ultimately, establishing clearer goals and enhancing the narrative flow of this chapter reiterates the need to maximise and optimise efforts invested in researching and leveraging information on hydrogen electrolyser technologies and their market dynamics effectively. Chapter Five will discuss the case of hydrogen in Zimbabwe.

CHAPTER FIVE

5.1. ENERGY CONUNDRUM: THE ZIMBABWEAN PERSPECTIVE

Chapter Five delves into the intricacies of the energy landscape in Zimbabwe, providing a contextual framework for understanding hydrogen production and its application within the nation. It provides a comprehensive exploration of the energy complexities, zooming in on hydrogen and illuminating its prospective role in the nation's energy future. Thus, the chapter presents a comprehensive overview of Zimbabwe's current energy mix, highlighting the historical reliance on traditional energy sources such as coal and biomass, alongside emerging renewable technologies. Each section is designed to illustrate the potential pathways for integrating hydrogen into the country's energy strategy while addressing significant barriers that must be overcome. The discussion from key informant interviews reveals the significant challenges faced in hydrogen production, including aging infrastructure, high operational costs, and reliance on imported gas, which hinders local production capabilities. This chapter further examines the regulatory landscape and existing energy policies that intersect with hydrogen initiatives, while reflecting on case studies from different sectors that illustrate both the potential and existing barriers to hydrogen adoption in Zimbabwe. The chapter, through its different sections, aims to elucidate the broader implications of transitioning to hydrogen energy, contributing to the discourse around best practices and the necessary steps towards achieving a sustainable hydrogen economy. The chapter concludes by considering the prospects of hydrogen as a viable energy source in Zimbabwe, addressing the need for policy frameworks, technological investments, and community engagement that can facilitate this transition.

5.2. Introduction

This chapter critically assesses Zimbabwe's energy landscape, focusing on hydrogen production and its implications for the future. It underscores a comprehensive analysis of the historical development of hydrogen production in Zimbabwe and its integration into the country's overall energy mix. It explores how hydrogen technology has evolved within the context of Zimbabwe's energy needs, economic factors, and policy environment, offering insights into prospects and challenges. The primary objectives include providing:

- ***An overview of Zimbabwe's Energy Mix:*** It highlights the historical reliance on traditional sources such as coal and biomass while recognizing the emergence of renewable technologies.
- ***Challenges in Hydrogen Production:*** It addresses significant barriers including aging infrastructure, high operational costs, and dependence on imported energy sources.
- ***Regulatory Landscape:*** It examines the current energy policies and their intersection with hydrogen initiatives.
- ***Case Studies:*** This section presents case studies from various sectors to illustrate both the potential and obstacles faced in adopting hydrogen energy technologies in Zimbabwe.

- ***Framework for Critical Analysis:*** This chapter adopts a SWOT and TOWS analysis framework to provide insights into the hydrogen sector, which is important for informing strategic steps necessary for transitioning to a sustainable hydrogen economy in Zimbabwe.

5.2.1. The key contextual research questions

The questions addressed in this chapter are:

- What is the historical trajectory of hydrogen technology development in Zimbabwe?
- How has the adoption of hydrogen production been influenced by local energy demands and resources?
- What is the role of hydrogen in Zimbabwe's current energy mix?
- What are the future challenges and opportunities for hydrogen as part of Zimbabwe's energy matrix?

Key informant interview data was collected through face-to-face interviews as a result of visits to the participants' sites by the researcher. The data was documented in the form of field diary notes and audio recordings that were conducted with consent of the participants.

5.3. Historical Overview of H_2 Technology Development in Zimbabwe

This section provides the timeline of Hydrogen Technology development in Zimbabwe. The timeline of hydrogen technology development in Zimbabwe illustrates a gradual progression from its industrial utilisation by the pioneering companies before the year 2000. There is increasing recognition of hydrogen's potential as part of the country's energy strategy. As Zimbabwe continues to explore and invest in hydrogen, the coming years may see significant advancements in technology, policy, and infrastructure development that could reshape its energy landscape.

5.3.1. Pre-2000: Industrial Use of Hydrogen

Before 2000, several Zimbabwean companies, particularly in the industrial sector, utilised hydrogen in various processes. For example, Sable Chemicals produced ammonia through the Haber process, which relied heavily on hydrogen as a key input (Banda, 2006). BOC Gases used to be the leading provider of industrial gases, including hydrogen used in welding, cutting, and other processes (Matibiri et al., 2010). Other companies, such as Olivine Industries, leveraged hydrogen in oil refining processes. Additionally, Lever Brothers, now Unilever and Zimbabwe Power Company (ZPC), incorporated hydrogen in their manufacturing and energy production processes, thereby establishing a strong foundation for investing in hydrogen for usage in the country's industrial landscape (Adebayo & Manda, 2013).

5.3.2. Early 2000s: Initial Interest in Hydrogen

With the advent of the 21st century, interest in alternative energy sources including hydrogen, began to emerge in Zimbabwe as the country faced economic challenges and energy shortages. Discussions about hydrogen's potential were more meaningfully incorporated in academic and industrial circles, with a special focus on its viability as a clean energy alternative (ZETDC, 2007).

5.3.3. 2005: First Hydrogen Research Initiatives

Universities and research institutions such as the University of Zimbabwe started conducting significant basic research on industrial-scale hydrogen production methods, including electrolysis and biomass gasification during this period. Those early-stage projects sought to assess the feasibility of utilizing Zimbabwe's renewable resources for hydrogen production (Chamboko et al., 2018).

5.3.4. 2010: Formation of Energy Policy Framework

The Zimbabwean government began developing a national energy policy framework that included provisions for renewable energy, indirectly fostering interest in hydrogen as part of the broader energy mix. However, practical initiatives in hydrogen technology remained limited at this stage (Ministry of Energy and Power Development, 2012).

5.3.5. 2015: International Collaborations

Zimbabwe engaged in international collaborations with organisations and countries experienced in hydrogen technology. These partnerships aimed to transfer knowledge, conduct pilot projects, and explore the potential for hydrogen fuel cell technology in various applications such as transport and off-grid energy systems (ZimTrade, 2015).

5.3.6. 2017: Strategic Reports on Renewable Energy Integration

During that time, the Zimbabwe Energy Regulatory Authority published reports that revealed growing advocacy for the integration of renewable energy sources, including hydrogen, into the national grid. This marked a significant shift toward recognizing hydrogen's potential role in addressing national energy access (ZERA, 2017).

5.3.7. 2018: Pilot Projects and Local Initiatives

Local companies, in collaboration with international partners, launched pilot projects focusing on hydrogen production using the electrolysis technology powered by solar energy. These initiatives aimed to demonstrate the technical viability and economic potential of hydrogen in Zimbabwe's renewable energy landscape (Munyati, 2018).

5.3.8. 2020: Policy Development and Investment Attraction

The Zimbabwean government proposed incentives to attract investments in renewable hydrogen projects as part of its commitment to achieving energy security and sustainability goals. This included support for research and development in hydrogen technology (World Bank, 2020).

5.3.9. 2021: Growing Awareness and Capacity Building

Increased awareness of hydrogen technologies led to the introduction of respective capacity-building programs in both the public and private sectors. A growing number of workshops and seminars were continuously being organised to educate stakeholders about the benefits and applications of hydrogen energy (Chirenda, 2021).

5.3.10. 2022: Evaluation of Green Hydrogen Potential

Comprehensive explorations were being conducted to evaluate the potential for green hydrogen production in Zimbabwe, particularly using the country's abundant solar and hydropower resources. Reports suggested that with the right investments and policies, Zimbabwe possessed the potential to become a regional leader in green hydrogen production (Soko & Vengeyi, 2022).

5.3.11. Strategic Roadmap for Hydrogen Economy: 2023

The Zimbabwean government and its key stakeholders in the industry were in the process of developing a strategic roadmap for the development of the national hydrogen economy. The roadmap emphasised research, investment, and collaborative efforts as pillars for integrating hydrogen into the energy mix, positioning it as a vital element of the future national energy policy (Zimbabwe National Hydrogen Strategy, 2023).

5.4. Lessons from the Evolution of H_2's Role in Zimbabwe's Energy Mix

Historically, Zimbabwean companies such as Sable Chemicals, BOC Gases, and Olivine Industries utilised hydrogen in their various industrial manufacturing processes such as ammonia production for fertilisers and oil refining (Banda, 2006; Matibiri et al., 2010). This early industrial use of hydrogen in Zimbabwe established a justified cause of hydrogen's role in the economy although wider recognition of its energy potential came later, particularly in response to fluctuating energy supplies and the global need for cleaner energy alternatives (ZETDC, 2007). Before Zimbabwe's independence in 1980, several large-scale hydrogen production facilities were established, notably the plants at Sable Chemicals and BOC Gases respectively. Following the independence, the Meteorological Services Department launched its hydrogen production facility, benefitting from a bilateral support agreement with France. However, the continued operation of this plant faced significant obstacles due to a lack of spare parts essential for maintenance, coupled with the inconsistent electricity supply throughout the country, which further complicated local hydrogen production efforts. The Meteorological Services Department utilised hydrogen balloons for weather forecasting purposes.

Meanwhile, various organizations have been acquiring portable hydrogen generators to meet their industrial requirements, particularly where smaller quantities of hydrogen are needed. These compact generators had the advantage of being easily operable, allowing for quick startup and shutdown while consuming relatively low levels of electricity. Despite these initiatives, the hydrogen produced domestically predominantly fell into the categories of brown and grey hydrogen. This is largely attributable to the fact that while the Kariba Power Station contributes hydroelectric power to the national grid, the Hwange Power Station generates electricity through thermal methods, adding brown-gray energy sources to the grid. Consequently, most electricity supplied to hydrogen generation facilities in Zimbabwe was derived from those less sustainable sources. Historically, the majority of the nation's older hydrogen generators employed alkaline water electrolysis technology that utilised water as a feedstock. In contrast, more recently installed generators have adopted proton exchange membrane (PEM) electrolysis.

This chapter offers an overview of the historical development of hydrogen production and utilisation in Zimbabwe. It also examined the policy frameworks governing renewable energy and the hydrogen sector in the country, alongside case studies of various organisations involved in hydrogen activities. Additionally, it highlights the challenges and opportunities associated with hydrogen production and use in Zimbabwe.

5.5. Current Energy Mix

This section provides an analysis of Zimbabwe's energy sources and the role of hydrogen. Recently, there has been a rise in interest in developing hydrogen so that it can be harnessed as part of Zimbabwe's broader energy security strategy. The government has initiated plans to diversify its energy sources, emphasising renewable energy integration (Ministry of Energy and Power Development, 2012). Pilot projects exploring hydrogen production from solar and biomass resources have emerged, reflecting a shift toward sustainable energy production practices (Munyati, 2018). Additionally, capacity-building initiatives are fostering awareness and expertise in hydrogen technology developments among local stakeholders (Chirenda, 2021).

5.6. Case Studies

This section provides a discussion of examples of hydrogen projects or initiatives in Zimbabwe. It further evaluates the implications of the reviewed case study findings to the future of hydrogen in the country's energy matrix. Evaluating the implications of findings regarding hydrogen's role in the energy matrix considering its potential contributions to sustainability, energy security, economic development, and energy technologies innovation. Below, is a discussion of these aspects of the study and a consideration of the future of hydrogen in the global and Zimbabwean energy contexts.

5.6.1. Implications of Findings

The implications of the findings are grouped into four categories as follows:

5.6.1.1. Sustainability and Environmental Impact Category

This section has two factors as noted below:

- **Reduction in Greenhouse Gas Emissions**: As a clean fuel, hydrogen offers significant potential for reducing greenhouse gas emissions when produced sustainably (i.e., green hydrogen through renewable electricity). Transitioning to hydrogen can help nations meet climate goals and contribute to global efforts against negative climate change. International collaboration assists in exchange of greener technologies between the global North and the global South with the propensity to fast track achievements of the global net zero targets.
- **Resource Efficiency**: Hydrogen can enhance the efficiency of energy systems by serving as an energy storage medium. It can store excess renewable energy and help balance supply and demand, particularly as renewable energy sources like solar and wind become more prevalent.

5.6.1.2. Energy Security Category

This section discusses two energy security aspects given below:

- **Diversification of Energy Sources**: Hydrogen can diversify the energy matrix, reducing dependence on fossil fuels and increasing resilience to global energy market fluctuations. This enhances national energy security by mitigating risks associated with energy supply disruptions.
- **Localized Energy Production**: Hydrogen production facilities can be established locally (e.g., from renewable sources such as solar and wind), reducing the need for lengthy supply chains and improving energy independence.

5.6.1.3. Economic Development Category

Economic development entails two main components discussed underneath:

- **Job Creation and Economic Growth**: Developing a hydrogen economy could generate new jobs in the production, distribution, and technology sectors. This is particularly relevant for nations like Zimbabwe, where economic diversification and job creation are critical challenges.
- **Investment Opportunities**: The growing global emphasis on renewable and hydrogen technologies presents investment opportunities for both local and foreign investors. These investments can stimulate technological advancements and infrastructure development.

5.6.1.4. Technological Innovation Capacity Category

The innovation capacities can be viewed in two ways as follows:

- **Research and Development**: The growing hydrogen sector can drive research and development activities, leading to technological innovations in hydrogen production, storage, and utilisation. This innovation ecosystem can spur advancements in other sectors, including transportation and heavy industry.
- **Demonstration Projects**: Pilot projects can serve as testbeds for new technologies and applications, helping to refine hydrogen technologies and demonstrate their viability at scale.

5.6.2. Future of Hydrogen in the Energy Matrix

Hydrogen is important in several sectors of the economic development matrix as follows:

5.6.2.1. Integration with Existing Energy Systems

- Hydrogen will increasingly be integrated into existing energy systems, serving as a bridge between traditional fossil fuels and renewable energy sources. This transition can occur through blending hydrogen with natural gas in pipelines or using hydrogen in fuel cells for electricity generation.

5.6.2.2. Building Infrastructure

- A significant expansion of hydrogen infrastructure, including production facilities, storage solutions, distribution networks, and fueling stations, will be essential. Investments in infrastructure development will facilitate the wider adoption of hydrogen technologies.

5.7. Emerging Markets and Applications

There will likely be a growing emphasis on development of specific policy frameworks and applications of hydrogen, including in the following sectors and appropriate policy and regulatory development framework expectations:

- ***Transport**:* Hydrogen fuel cells play a key role in decarbonizing heavy transport (buses, trucks, and ships) where electrification poses challenges.

- ***Industry**:* Hydrogen can replace fossil fuels in industrial processes, particularly in sectors like steelmaking and chemical production.

- ***Power Generation**:* Hydrogen can be used in gas turbines for electricity generation, offering a flexible solution for utilities to meet peak demand.

- ***Global Market Development**:* The hydrogen market is expected to grow significantly, with many countries and companies vying for leadership in hydrogen technologies. International collaboration on hydrogen trade (exporting green hydrogen) could thus, become a vital aspect of the global energy dynamics.

- ***Policy and Regulatory Frameworks**:* Supportive policies, incentives, and regulations will play a crucial role in the hydrogen economy's growth. Governments must create an enabling environment that promotes research, development, and deployment of hydrogen technologies.

5.8. Challenges and Other Key Considerations

Despite its potential, the hydrogen sector faces challenges such as high production costs (especially for green hydrogen), storage infrastructure and safety, and transportation mechanisms, and the lack of a robust regulatory framework and standards. Overcoming these challenges will require innovation, strategic investment, political will and collaboration among various stakeholders. The findings regarding hydrogen's evolving role in energy systems emphasise its potential as a cornerstone of a sustainable, resilient, diverse energy future. For countries like Zimbabwe, embracing hydrogen technology can address energy security and economic challenges while contributing to global climate goals. Moving forward, strategic initiatives involving investment, policy support, and collaboration are crucial to unlocking the transformative potential of hydrogen in the energy matrix.

5.9. CPI: Implications on Zimbabwe's H_2 Potential

Hydrogen is increasingly recognised as a crucial component of the global transition to clean energy. For Zimbabwe, which seeks to become a player in the emerging hydrogen economy, the Corruption Perception Index (CPI) proves to be an essential factor that influences investment, project development, and overall success in the economy and, specifically, the energy sector. This section of the chapter discusses Zimbabwe's CPI, the implications of corruption on hydrogen initiatives, and the steps necessary to foster a conducive environment for hydrogen production and innovation.

5.9.1. Corruption Perception Index (CPI)

The Corruption Perception Index (CPI) is a measure that evaluates the perceived levels of corruption in public sectors across different countries. Zimbabwe scores very lowly on the CPI scale, with a 22 out of 100 in recent reports, ranking it 157th out of 180 countries (Trancparency International, 2024). This score buttresses a widespread perception that corruption is a significant barrier to governance and economic development, posing particular challenges for sectors requiring substantial investment and regulatory oversight, such as hydrogen. This low perception of integrity is a disincentive for domestic and international investment, especially in capital-intensive industries such as hydrogen. The relationship between corruption and economic development is profoundly intricate, impacting investor confidence, resource allocation, and the ability of the state to implement policies effectively. Corruption in Zimbabwe is not confined to high-ranking officials or political figures; it permeates various levels of law enforcement, the judiciary, and regulatory agencies. These sectors are pivotal for ensuring that rules governing investments, especially in emerging technologies like hydrogen, are upheld (Muchena, 2024).

5.9.2. Implications of Corruption on Zimbabwe's Hydrogen Initiatives

The following are the implications of corruption on Zimbabwe's hydrogen initiatives.

5.9.3. Investment Deterrence

The low CPI score can deter local and foreign investors crucial for launching hydrogen projects. Investors often seek stable environments free from corrupt practices. Fear of bureaucratic hurdles, bribery, and a lack of clear regulatory frameworks may lead to decreased interest in Zimbabwe's hydrogen sector.

5.9.4. Misallocation of Resources

Corruption can lead to diverting funds intended for hydrogen initiatives toward personal gains or less beneficial projects. Such misallocation could stall efforts to develop renewable energy projects, including hydrogen production facilities that rely on solar and other sustainable sources.

5.9.5. Undermining Partnerships

Building partnerships with international organisations, research institutions, and private sector players is critical for developing hydrogen technologies. Corruption can erode trust among stakeholders, making collaboration difficult. Potential partners may shy away from engagements if they perceive risks tied to corrupt dealings.

5.9.6. Regulatory Barriers

The energy sector requires a robust regulatory framework fostering innovation while ensuring international standards compliance. In an environment marked by corruption, regulatory requirements may be exploited for personal advantage, leading to inconsistent policy applications that could hinder the urgent development and deployment of hydrogen technologies.

5.9.7. Opportunities in Zimbabwe's Hydrogen Sector

Despite the significant challenges posed by corruption, Zimbabwe possesses unique opportunities to advance its hydrogen potential:

- ***Rich Renewable Resources**:* Zimbabwe has abundant solar and hydro resources ideal for producing green hydrogen. If effectively harnessed, these resources can position Zimbabwe as a competitive player in the hydrogen market.
- ***Regional Cooperation**:* Collaborative initiatives within the Southern African Development Community (SADC) focused on hydrogen can help streamline efforts and establish best practices. However, these partnerships can only flourish in a corruption-free environment.

- ***Government Reforms**:* The Zimbabwean government has expressed interest in reforming energy policies. Strengthening governance and transparency within these reforms can create a more favorable climate for hydrogen investment and development.

5.9.8. Mechanisms for Enhancing Transparency and Reducing Corruption

To optimise Zimbabwe's hydrogen potential, it is crucial to tackle the underlying issues of corruption through:

- ***Strengthening Legal Frameworks**:* Implementing stronger anti-corruption laws and ensuring accountability for public officials can help restore investor confidence.
- ***Enhancing Transparency**:* Establishing clear guidelines for energy procurement and project approvals can reduce opportunities for corrupt practices. Transparent bidding processes and public reporting on project status can promote stakeholder trust.
- ***Capacity Building**:* Investing in capacity-building programs for regulatory bodies to enhance their understanding of the hydrogen sector and improve governance can further deter corruption.
- ***Engaging Civil Society**:* Encouraging the involvement of civil society and local communities in monitoring energy projects can enhance accountability. Their engagement can ensure that hydrogen initiatives benefit the broader population rather than just a select few.

Given the country's renewable energy resources and strategic location, Zimbabwe has significant potential for hydrogen development. However, to unlock this potential, addressing the challenges posed by corruption through robust reforms and transparent practices is essential. By focusing on improving the CPI score and tackling corrupt practices, Zimbabwe can foster an environment that attracts investment, promotes sustainable energy development, and positions itself as a key player in the emerging hydrogen economy.

5.9.9. Lessons Learnt

The key lessons drawn from this study entail the need for:

- ***Diversification of Energy Sources:*** The evolution of hydrogen production underscores the importance of diversifying energy sources. By incorporating hydrogen into the energy mix, Zimbabwe can enhance energy security and reduce dependency on traditional fossil fuels. This diversification is crucial for mitigating the impacts of resource volatility.
- ***Collaboration and Partnerships:*** International collaborations with countries experienced in hydrogen technology is pivotal. These partnerships facilitate knowledge transfer, providing the necessary expertise to develop local hydrogen initiatives (ZimTrade, 2015). Leveraging

international support can accelerate research initiatives and the deployment of hydrogen technologies in Zimbabwe.

- ***Policy and Regulatory Frameworks:*** Establishing favorable policies and regulatory frameworks is essential for cultivating a hydrogen economy. Strategic policies that incentivise investment in hydrogen production and infrastructure development are necessary to attract local and foreign investors (World Bank, 2020).
- ***Focus on Research and Innovation:*** Continued investment in research and development is critical for advancing hydrogen technologies. As demonstrated by early research initiatives, innovative approaches to hydrogen production, storage, and utilisation can lead to cost reductions and improved efficiency (Chamboko et al., 2018).
- ***Public Awareness and Engagement:*** Increasing public understanding of hydrogen's benefits and potential applications is vital for gaining community support and fostering grassroots involvement in energy initiatives (Chirenda, 2021). Public engagement helps align renewable energy projects with local needs and concerns.
- ***Sustainability Considerations:*** Integrating hydrogen into the energy mix should prioritize sustainability. Evaluating the environmental impact of hydrogen production processes ensures that the shift to hydrogen does not compromise ecological integrity. Emphasising green hydrogen production methods aligns with global sustainability goals.

An Analysis of Law Enforcement Agents, Judiciary, and Regulatory Framework leaves a lot to be desired particularly regarding the following:

- Law Enforcement and Police: The police force is traditionally viewed as a front-line institution responsible for law enforcement and governance. However, in Zimbabwe, allegations of police misconduct, bribery, and collusion with corrupt officials have resulted in a lack of public trust. This skepticism extends to investors, who may fear bureaucratic interference that undermines investment projects related to hydrogen. The misapplication of laws pertaining to energy production can also arise, complicating the environmental assessments and permitting processes necessary for new renewable energy projects.
- Judiciary: A robust and independent judiciary is vital for fostering an environment conducive to investment. However, in Zimbabwe, perceptions of judicial corruption and inefficiency can undermine the enforcement of contracts and the protection of property rights. For hydrogen initiatives, this could mean that involved parties may struggle to ensure that agreements are respected, leading to uncertainties that deter investment. If disputes arise, the judiciary's tendency

to prioritize political interests over impartiality may further discourage stakeholders from entering the market.

- Regulatory Agencies: Regulatory bodies ensure compliance with laws and standards that safeguard public interest. In Zimbabwe, however, these agencies have often succumbed to corruption and external pressures, resulting in inconsistent enforcement of energy policies. This creates an unpredictable regulatory environment where hydrogen initiatives may be subject to arbitrary decisions, undermining the trust necessary for long-term investments in the sector.

For Zimbabwe, strategic investment, innovation, political will, and collaboration become essential in confronting these challenges. The importance of a stable, corruption-resistant environment cannot be overstated; improving governance could enhance investor confidence and promote the development of the hydrogen economy.

5.9.10. Future Prospects

Looking forward, hydrogen holds significant potential for Zimbabwe's energy landscape. Studies indicate that with the country's abundant solar and hydropower resources, Zimbabwe could position itself as a regional leader in green hydrogen production (Soko & Vengeyi, 2022). As the global hydrogen market expands, Zimbabwe can capitalise on this opportunity to attract investments, create jobs, and enhance energy independence.

5.10. SWOT Analysis of the Hydrogen Sector in Zimbabwe

The SWOT analysis serves as a structured framework for evaluating the strengths, weaknesses, opportunities, and threats, and in this case, the analysis concerned hydrogen production in Zimbabwe.

5.10.1. Strengths

- ***Natural Resources:*** Zimbabwe possesses abundant water resources, crucial for electrolysis, which is required for green hydrogen production.

- ***Existing Institutions:*** Historical production facilities, such as those installed at Sable Chemicals and BOC Gases, provide a foundation for revitalising the hydrogen sector.

- ***Government Support:*** Initiatives like the National Renewable Energy Policy indicate governmental interest in furthering renewable energy development, including hydrogen technologies.

5.10.2. Weaknesses

- ***Outdated Infrastructure:*** Much of the current hydrogen production technology is antiquated and fails to align with modern practices, adversely affecting efficiency and global market competitiveness.
- ***High Production Costs:*** Electrolysis, currently reliant on grid electricity, incurs high operational costs, which significantly undermine the market viability of hydrogen production (Chance, 2021).
- ***Limited Market Demand:*** The shrinking industrial base and reduced local demand for hydrogen have reversed producers' economic viability.

5.10.3. Opportunities

- ***International Markets:*** Targeting European and global hydrogen markets could provide new economic opportunities and foster a sustainable export industry.
- ***Technological Innovation:*** Investment in emerging technologies can position Zimbabwe as a significant player or leader in renewable energy.
- ***Policy Development:*** The absence of a dedicated hydrogen policy in Zimbabwe presents an opportunity for the government to develop an enabling environment for investment and growth in the hydrogen sector by enacting contemporary and inclusive legislation.

5.10.4. Threats

- ***Energy Scarcity:*** The ongoing energy crisis, characterised by frequent outages, threatens the operational capacity of any hydrogen production facility in the country.
- ***Competition from Imports:*** Local producers face significant competition from imported hydrogen and hydrogen-containing products, undermining their market share.
- ***Political and Economic Instability:*** Economic challenges underpinned by sanctions and policy uncertainty can deter foreign investment in the hydrogen sector.

5.11. TOWS Matrix Analysis: Strategic Actions for Zimbabwe's H_2 Sector

H_2 TOWS Matrix	Opportunities (O)	Threats (T)
Strengths (S)	**SO Strategies**	**ST Strategies**
1. Abundant water resources for electrolysis	1. **Leverage Existing Resources:** Utilise existing facilities and technology at Sable Chemicals and BOC Gases to enhance training programs and skills development in hydrogen production and management.	1. **Contingency Planning:** Develop robust contingency plans and risk management strategies to ensure consistent hydrogen production despite ongoing energy shortage and stability issues.
2. Established infrastructure and institutions promoting renewables.	2. **Collaborative Innovation:** Forge partnerships with international firms to adopt and localise cutting-edge hydrogen technologies and processes, to foster innovation and efficiency.	2. **Market Monitoring and Adaptation:** Establish a dedicated team to constantly monitor international hydrogen market trends, to ensure local producers can swiftly adapt their strategies to remain competitive against imported products.
3. Government interest in promoting renewables.	3. **Public-Private Partnerships (PPPs):** Establish PPPs to incentivise investments in green hydrogen initiatives, mobilising funds and expertise for large-scale projects.	3. **Policy Advocacy:** Actively advocate for supportive policies that protect local producers from external competition and promote hydrogen energy at a national scale.
Weaknesses (W)	**WO Strategies**	**WT Strategies**
1. Obsolete and inefficient production technologies.	1. **Commit to Modernization:** Direct resources towards modering outdated hydrogen production facilities, attracting	1. **Optimise Operational Efficiency:** Conduct a comprehensive review of production processes to

	foreign investments to incorporate state-of-the-art technologies (Mlambo, 2017).	identify and rectify inefficiencies, aiming to reduce operational costs significantly (Oertzen, 2021).
2. High operational expenses that undermine market competitiveness.	2. **Pursue Technology Development Initiatives:** Launch initiatives focused on local research and development to devise cost-effective hydrogen production methods and reduce dependence on imported technologies (Imasiku et al., 2021).	2. **Enhance Energy Supply Security:** Invest in renewable energy projects, particularly solar power, to support hydrogen production, thus reducing reliance on the national grid and alleviating energy scarcity issues (Musariri, 2015).
3. Insufficient domestic demand for hydrogen.	**Broaden Market Engagement:** Initiate awareness and marketing campaigns to promote the advantages of hydrogen among potential local industries, fostering new applications and sectors for hydrogen use (Ngila, 2022).	3. **Expand Hydrogen Utilisation:** Work on broadening hydrogen applications across various sectors, such as transportation and residential energy, to develop new markets and counterbalance domestic demand limitations (Chance, 2021).

5.12. Zimbabwe Country Profile

Zimbabwe is strategically located in Southern Africa, bordered by Zambia, Mozambique, South Africa, Botswana, and the Zambezi River. Its capital is Harare.

Table 5.1: Summary of Zimbabwe Country Profile

Capital:	Harare	Region:	Sub-Saharan Africa
Total Area:	390,760 km²	Population:	15,475,000 (2023)
Rural Population:	Approx. 67% (2023)	GDP (current US$):	$20.12 billion (2022)
GDP Per Capita (US$):	$1,300 (2022)	Electricity Access (%population):	50% (2021)
Energy Imports Net (%energy use):	15% (2021)	Fossil Fuel Consumption (% total):	49% (2020)

Source: World Bank, African Development Bank, and CIA World Factbook (latest data up to 2023).

Notes on Data:
Population: The estimated 2023 population figure was updated based on recent demographic trends.
GDP: The 2022 GDP figure reflects recent economic assessments.
Electricity Access: The figure for electricity access was updated to reflect a slight decline in access as of 2021.
Energy Imports and Fossil Fuel Consumption: These figures have been adjusted to reflect the latest available estimates and trends observed in energy consumption.

5.13. Energy practice, mix and prospects in Zimbabwe

Zimbabwe uses different energy sources and those are discussed in the subsections that follow:

5.14. Zimbabwe Energy Profile

The energy supply options for Zimbabwe are a mixture of hydroelectricity, coal, and renewable sources. The Zimbabwean industry largely relies on coal and hydro and thermal electric power which sustains baseload for continuous operation. In rural parts of the country, 80-90% of the people depend on wood fuel. Food processing tasks like grain milling are usually carried out with diesel-powered generators and grid electricity-powered systems. During research, the national electricity generation capacity stood at 1400 MW, and the national peak demand was 2400 MW. The suppressed demand was 1600 MW, while the national deficit was +/-1000 MW, augmented through imports from neighbouring countries and other demand-side management strategies (Musariri, 2015). Five key high-energy-demand sectors in Zimbabwe are agriculture, industry and mining, commerce and services, transport, and urban and rural households.

Zimbabwe has access to various energy forms, including solar, biomass/bagasse, coal and petroleum, diesel, LPG gas, and electrical power from hydro and thermal power stations (Madya, 2023). Paraffin, wind power, and geothermal energy are also used countrywide, but relatively not at a large scale. Urban areas get most of their energy from the national supplier ZETDC while the rural areas mainly use biomass energy.

The national grid is well developed, with efforts after 1980 to extend supplies to rural homesteads, businesses, and administrative government areas. Most of Zimbabwe's electricity is produced at the Kariba Dam Hydroelectric Power Station (about 750 MW), at Hwange Thermal Power Station which has an installed capacity of 920 MW, and at three other minor coal-fired stations. In the same respect, apart from the Kariba Dam Hydroelectric Power Station, there is still quite a lot of hydropower potential, especially along the Zambezi River.

Solar Power has enormous, small, and large-scale generating capacity potential, while wind and biogas energy are some possible options. In Zimbabwe, as indicated in Figure 5.1 below, hydroelectric power continues to account for around 4% of the energy generated in the country. Nevertheless, 5% is imported, and 66% of the total energy comes from biomass, 19% from coal, and 6% from petroleum products (Get.Invest, 2019 and Musariri, 2015).

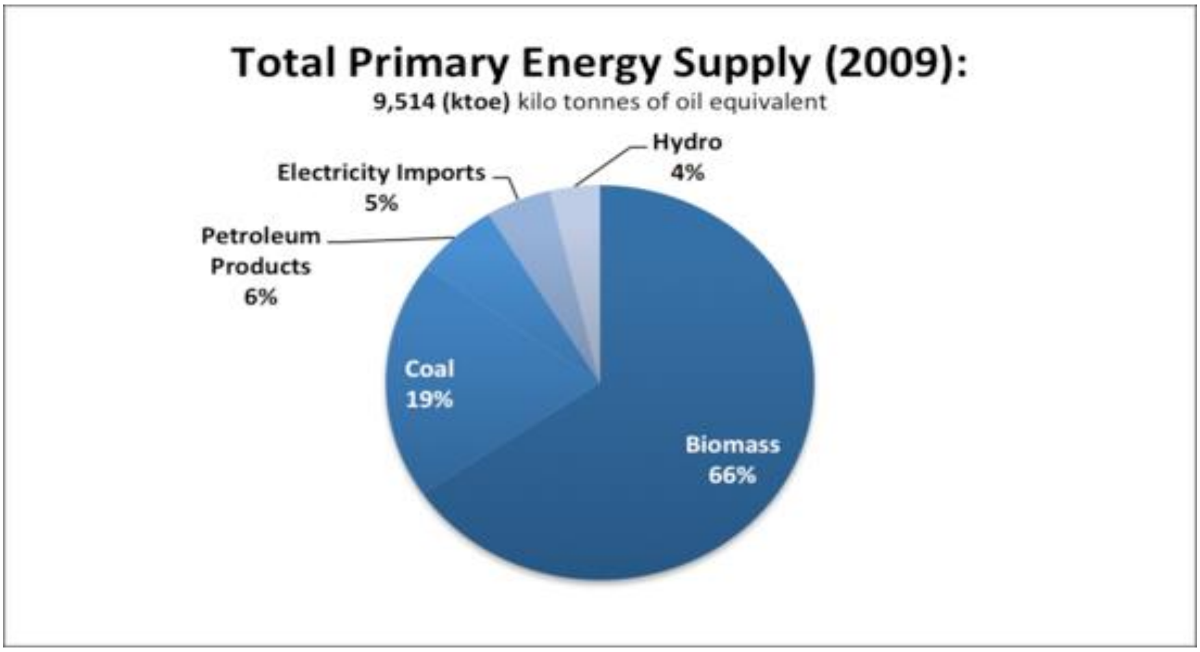


Figure 5.1: Total Primary Energy Supplies (**Source:** Adapted Mukuvisi Woodlands, 2014).

Solar energy has become familiar across the country in industries and households, with some using it as a supplement and some as the sole energy source. Many private companies and organisations have built or purchased facilities for high power generation from 0.1 MW to 50 MW (Madya, 2023). As of August 2022, about 30 operational independent power producers were registered with the country’s energy regulator ZERA, as summarised in Table 5.2 below (ZERA, 2022).

Table 5.2: ZERA licensed independent power producers (**Source:** Adopted from ZERA, 2022).

POWER STATION	MW	TECHNOLOGY	LOCATION
Triangle Power Station	35	Bagasse/Thermal	Lowveld
Hippo Valley Estate Power Station	39	Bagasse/Thermal	Lowveld
Green Fuel Ethanol Plant	18.3	Bagasse/Thermal	Chisumbanje
Nyanyana South Solar plant	1.2	Solar PV	Kariba
Econet Willowvale Solar Plant	0.45	Solar PV	Willowvale, Harare
SAZ Solar Plant	0.19	Solar PV	SAZ Head office, Harare
Schweppes Harare Solar Plant	1	Solar PV	Southerton, Harare
Nottingham Estates Solar/ Diesel Power Plant	2.25	Solar PV/Diesel	Nottingham Estates, Beitbridge
Mutual Gardens Solar Plant	0.648	Solar PV	Mutual Gardens, Harare
Econet Msasa Solar Plant	0.105	Solar PV	Mutare Road, Harare
Econet Graniteside Solar Plant	0.101	Solar PV	Graniteside, Harare
Econet Mutare Solar Plant	0.108	Solar PV	Mutare
Luxaflor Roses Solar Plant	0.118	Solar PV	Mazowe District
Surrey Abattoir Solar Plant	0.117	Solar PV	Surrey Farm, Marondera,
Schweppes BBJ Factory Solar Plant	0.564	Solar PV	Beitbridge, Matabelelend South
Tanganda- Ratelshoek Solar Plant	1.8	Solar PV	Ratelshoek Estates, Chipinge
Dormervale Farm Solar Plant	0.382	Solar PV	Dormervale Estate, Marondera
Cross Mabale Power Plant	5	Solar PV	Cross Mabale, Hwange
Pungwe Mini Hydro (B) power station	15.25	Hydro	Honde Valley, Manicaland
Pungwe C Power Station	3.72	Mini hydro	Pungwe River, Honde Valley
Hauna Power Station	2.3	Mini hydro	Ngarura River, Honde Valley
Claremont Power Station	0.3	Mini hydro	Claremont States, Nyanga
Tsanga B Power Station	2.67	Mini hydro	Tsanga River, Nyanga
Nyamingura Power Station	1.1	Mini-Hydro	Honde Valley, Manicaland
Kupinga Power Station	1.6	Mini-Hydro	Rusitu Valley, Chipinge
Centragrid Power Station	2	Solar PV	Penrose Farm, Nyabira
Riverside Power Station	2.5	Solar PV	Musvaire, Mutoko
Duru Mini Hydro power plant	3.8	Hydro	Duru, Honde Valley
Pungwe Mini Hydro (A) power station	2.75	Hydro	Honde Valley, Manicaland
Zimbabwe Zhongxin Electrical Energy Thermal Power Station	50	Coal-fired /Thermal	Deka Bridge Farm, Hwange

To boost the use of renewable energy, Zimbabwe banned the export of raw lithium in January of 2023 to promote domestic processing of the raw lithium into batteries. Zimbabwe has the highest deposits of lithium in Africa, and it hopes to meet 20% of the world's lithium demand (Ngila, 2022). Lithium is a valuable component of electronic batteries. Proven lithium deposits are found in Goromonzi, Kamativi, Kadoma, Bikita, Mudzi, Chegutu, Fort Rixon, Harare, Hwange, Bindura, Rushinga, Mutare, Mutoko, Buhera, Mberengwa and Insiza. Bikita mine has the most prominent established lithium reserves in Zimbabwe, with a reserve of 10.8 million tonnes (Nyeve, 2023).

5.15. Energy sources

This section comprises a discussion of the various energy sources in Zimbabwe.

5.15.1. Biomass

In Zimbabwe, firewood is a major source of household cooking and heating energy for roughly 90% of the rural population (REEEP, 2012), with consumption surpassing supply in many of the most densely populated provinces. Demand outnumbers sustainable forest output since in Zimbabwe, a factor of 1.5 is the prevailing land area per capita. The diminishing forest stock threatens food and energy security. The biofuels industry holds a lot of promise, and over 1.3 million tonnes of bagasse are used to generate electricity for the two sugarcane mills in southern Zimbabwe (Mbohwa, 2006).

Border Timbers, a private company for timber in Manicaland province produces some of its power from wood waste (Border Timbers, 2017). However, no data on the amount of power they generate was published at the time of the research. Some other private companies that produce their power from biomass are Hippo Valley Estates (Mtunzi *et al*., 2012) and Triangle Estates, which produce their energy from bagasse (Mbohwa, 2006 and Fukuda, 2003).

5.15.2. Hydropower

There are several hydropower generation stations in Zimbabwe, and these are discussed below.

5.15.2.1. Kariba Hydro Power station

Construction of the Kariba hydropower station began in 1956, with engineers mining a cavern on the dam wall to house a power station about 174 meters below the land surface. The first generator was commissioned in 1959 followed by 5 others that became fully operational in 1962, to make a total generation capacity of 666 MW. The station was upgraded to 125 MW per unit, making the total installed capacity 750 MW (ZPC, 2023).

In 2014, ZPC embarked on a project to extend the existing plant by adding two more units with a total generation capacity of 300 MW. The project was completed and commissioned in March 2018, making the Kariba South Power Station the biggest power generation plant in Zimbabwe with a total generation capacity of 1050 MW. However, as of January 2023, Kariba South Power Station was producing an average of 380 MW due to very low water levels in the Kariba dam (Ibid) and even less, as was the case around September 2024 when the output fell to 250MW.

5.15.2.2. Batoka Gorge Hydroelectric Power Station

The Batoka Gorge Hydroelectric Power Station is a proposed 2400 MW hydroelectric power station planned for the Zambezi River that is between Zambia and Zimbabwe (Hill and Naidoo, 2019). The proposed power station was planned to be located on the Zambezi River, approximately 54 kilometres (34 miles) downstream of Victoria Falls, straddling the border between Zambia and Zimbabwe (Lusaka Times, 2013). The proposed plan comprises two power plants, with an installed capacity of 1200 MW each, one on the Zambian side and another on the Zimbabwean side (COMESA, 2014).

The project was supposed to be implemented under the Zambezi River Authority administration, a binational organisation mandated to operate, monitor, maintain, and exploit the full potential of the Zambezi River. As of July 2018, the projected development cost was estimated at US$4.5 billion (Mukarati, 2018). According to Bloomberg News, the construction contract was awarded to a consortium of General Electric of the United States and Power Construction Corporation of China in June 2019 (Hill and Naidoo, 2019).

Construction was expected to take ten to thirteen years. However, there were concerns by the Zambezi local community that the project would destroy the Batoka Gorge tourism, which employed thousands of local individuals through whitewater rafting. It was also viewed that the dam would not provide electricity directly to the local rural population, as the electricity was feared would be exported to the Southern African Power Pool. The Southern African Power Pool is a cooperation of the national electricity companies in Southern Africa under the auspices of SADC (Takouleu, 2019).

5.15.2.3. Tokwe Mukosi

Tokwe-Murkosi was scheduled to have a power plant expected to generate 15 megawatts (MW) at peak and 6 MW at lowest peak, beginning in June 1998 (Chenga, 2014). The power generated was expected to be sold to the government-owned Zimbabwe Electricity Transmission and Distribution Company (ZETDC). Locally, the power was expected to be used to drive anticipated fishery projects, hotels, and lodges as the area was earmarked for development into a tourism resort (Sunday Mail, 2017).

5.15.2.4. Lake Mutirikwi

A 5-megawatt Power Plant worth $14,2 million was being constructed at the Mutirikwi Dam wall. The plant had to be called the Great Zimbabwe Hydropower Station, designed with provision for 2 turbines of 2.5 MW capacity each. Power evacuation from the dam was planned to be via a 25 km 33 kV transmission line, to the Kyle substation and it was scheduled to start feeding into the national grid by July 31, 2023 (Mtembo, 2022). Another 5 MW plant was planned for Manyuchi Dam (Kuhudzai, 2022). Completion of Tokwe Mukosi, Great Zimbabwe, and Manyuchi Dam Power Stations were designed with the potential to contribute up to 25 MW of power, which was anticipated to be more than enough for Masvingo, which was using approximately 22 MW per day in 2017 (Sunday mail, 2017).

5.15.3. Oil and natural gas

Concerning oil, Zimbabwe has remained entirely reliant on imports (REEEP, 2012). However, two large natural gas deposits were found in Muzarabani and as coal bed methane in Matabeleland north (The Herald, 2022). An Australian private company (Invictus) was awarded a license to explore and drill oil and gas in Zimbabwe (Sibanda, 2021). In September 2022, Invictus began drilling gas under the Mukuyu-1 project, which had prospects of 845 million barrels of gas condensate on 360,000 hectares in Muzarabani. Invictus also found 6.5 trillion cubic feet of oil in Muzarabani, making it the largest oil reserve in Africa (The Herald, 2022).

5.15.4. Coal

In Zimbabwe, coal is essential for producing electricity and is sometimes used for heating and cooking. As of January 2023, Hwange Thermal Power Station produced an average of 365 MW, while Munyati Power Station produced an average of 17 MW per day (ZPC). According to WEC (2013), the proven recoverable reserves of coal in 2011 were 0.5 billion tonnes of bituminous, including anthracite coal, and ranked 38 on the global list of coal deposits (Table 5.3). In 2021, the total production of bituminous coal was 3.239 million tonnes (CEIC, 2021). Despite the large deposits, coal contributes only 0.28538% of Zimbabwe's GDP (World Bank, 2020).

Zimbabwe and Chinese companies were building new coal infrastructure for thermal power stations to mitigate the chronic power shortages (Mukeredzi, 2020). Zimbabwe Zhongxin Electrical Energy (ZZEE), a joint venture between China and Zimbabwe, constructed a 50MW power plant to raise it to 430 MW. Dinson Colliery, a coal-mining subsidiary of Tsingshan Holding Group, was constructing a US$300 million coking plant. However, in 2020, some funds were pooled through China Gezhouba Group Company and RioZim Energy to construct a 2,800 MW thermal power station in Gokwe. These funds were later diverted, raising concerns about whether any such deals will ever materialise (Banya and Reid, 2022).

Table 5.3: Coal volumes from Zimbabwe

	Tons	Global Rank
Coal Reserves	553,359,620	38th in the World
Coal Production	2,976,237	37th in the World
Coal Consumption	3,338,555	53rd in the World
Coal Deficit	-412,318	
Coal Imports	173	
Coal Exports	47,903	
Net Exports	47,729	

*(**Source:** Adopted from WEC, 2013).*

5.16. Coal Contribution to GDP in Zimbabwe

- ***Industry Overview**:* Zimbabwe has significant coal reserves, primarily located in the Hwange region. The coal mining sector is a crucial part of the country's mining industry, and it is also one of the largest sectors in Zimbabwe, contributing significantly to employment and economic output.
- ***Economic Contribution**:* While exact figures may vary year by year, it is generally estimated that the mining sector (which includes coal mining) contributes around **10% to 15%** of Zimbabwe's total GDP. Within this sector, coal can account for a varying portion, often estimated between **2% to 5%** of GDP directly, depending on factors such as production levels, market prices, and the overall economic context.
- ***Electricity Generation**:* Coal is a primary source of electricity in Zimbabwe. The Zimbabwe Power Company relies heavily on coal-fired power plants, which means that the economic impact of coal extends beyond mining alone, contributing indirectly to GDP through sectors like electricity generation and manufacturing.

As investment in renewable energy grows and Zimbabwe focuses on diversifying its energy sources, the direct contribution of coal to GDP may fluctuate. Global shifts toward cleaner energy sources might also influence local coal demand, impacting economic contributions.

5.17. Solar Energy

The solar PV business is a growing industry with potential solar insolation of 5.7 kWh/m2/day (REEEP, 2012). However, it has not been widely exploited. Although solar PV has a technical capacity of over 300 MW, only 3 MW was utilised as of 2012 (REEEP, 2012). Schools, hospitals, and households in rural areas mostly use solar energy. Exploiting this potential might significantly increase the local population's access to electricity and help Zimbabwe reduce its greenhouse gas emissions (Tswami, 2022).

Zimbabwe planned to build 1 GW worth of solar farms, which had to feed into the National Grid by 2025 (Santos, 2022). The Zimbabwean government promised guaranteed viable power tariffs to independent solar projects under the Government Implementation Agreement (GIA). This action was meant to comprise a project development support plan, a power purchase contract, and a deal with Zimbabwe's Reserve Bank for assured dividend payments and repayment of foreign loans to outside lenders and investors (Ibid).

5.18. Wind and Geothermal Energy

In general, Zimbabwe's efforts to produce wind energy are limited by the comparatively low wind speeds of around 3.5 m/s. However, there are some places such as the Eastern Highlands, which have a 300 km length of mountains, and Bulawayo, which has seen recorded speeds of between 4 and 6 m/s (REEEP, 2012). Only off-grid applications were being used for this resource. Zimbabwe's proximity to the Great Rift Valley may imply that geothermal energy may also be present in the country. However, more studies must explore this area (REEEP, 2012).

5.19. Problems in the Energy Sector

Although national electricity access stands at 40%, access to electricity in rural areas (19%) is much lower than in urban areas (80%) due to the prohibitive costs of extending national electricity grids (Musariri, 2015). Capacity further remains a significant concern in Zimbabwe. All coal-fired stations in Zimbabwe needed major upgrades. They were continuously experiencing frequent production stops or producing no electricity. This has led to frequent and long-lasting blackouts in the country. Energy imports from neighbouring countries have also remained inadequate in solving the under-capacity problem. As a result, power outages continued to affect the economic performance of industries and services. Small-scale power generators are excessively used in the country to ease this situation (Get.Invest, 2019 and Musariri, 2015).

5.20. Specific Renewable Energy Strategies

The Zimbabwe Ministry of Energy and Power Development (www.energy.gov.zw) is delegated with the overall responsibility for energy and power development in Zimbabwe. The terms of reference include policy formulation, performance monitoring, and regulation of the energy sector, as well as research, development, and promotion of new and renewable energy sources. The Ministry supervises and oversees the performance of the energy parastatals, namely ZESA Holdings and NOCZIM.

The Rural Electrification Fund (REF) was resumed in Zimbabwe in April 2018. It was slowly mooted in 1983, started in 1987, and funded in 1989. Through this fund, Zimbabwe announced its plan to electrify all public institutions such as schools, government extension offices, and other Government departments for free. REF offers a 100% capital subsidy to public institutions. The institutions were only paying for the internal wiring of their buildings and connection fees. In schools, the government prioritised electrification of the administration block, science laboratories, and computer laboratories while internal wiring and connection fees were also subsidised (Rural Electrification Fund, 2022).

Since 2002, REF has electrified more than 2,699 primary schools, 1,359 secondary schools, 874 rural health centers, 411 Government extension offices, 244 chiefs' households, 952 business centres, 774 small-scale farms, 1175 villages, and 803 other institutions. In July 2019, Zimbabwe removed import duties on all solar-related products, from batteries to cables.

The government also introduced a new mandate that all newly constructed infrastructure should have solar systems installed (Energypedia, 2011). This move was aligned with the government's national renewable policy that sought to promote local production and importation of solar-related equipment. The Zimbabwean government aimed to produce 1575 MW of power from solar by 2030, and the government has also rolled out innovation mechanisms, such as net metering and the feed-in tariff for clean energy, to enable Independent Power Producers to add their excess electricity to the national grid (Rural Electrification Fund, 2022).

The Rural Electrification Fund Act (13:20) created a Rural Electrification Agency (REA) (www.rea.co.zw) mandated to ensure total electrification of all rural areas, funded by electrification levies and government stipends. The main functions of the agency are the planning of projects, raising and accounting for rural electrification funds, and the monitoring and evaluation of the projects that were being implemented.

The Scientific and Industrial Research and Development Centre (SIRDC) in Zimbabwe conducts research and development in renewable energy and energy conservation. SIRDC has been researching hydrogen production but has not made much headway because of limited research funding. The Forestry Commission is active in woody biomass as their mandate covers all state forests, a major source of fuel wood in the country. The University of Zimbabwe's Department of Mechanical Engineering and the Chinhoyi University of Technology run programs in renewable energy. The Harare Polytechnic has been conducting trials on Jatropha Curcas and biodiesel since around 2005 (Karavina, Zivenge, Mandumbu and Parwada, 2011).

The Jatropha Curcas program in Zimbabwe was implemented to produce biodiesel and bioethanol from the Jatropha feedstock. The program was nevertheless hurried and implemented in a national legal and policy framework vacuum without a foundation of in-depth research on the matter (Mubonderi, 2012).

Historically in the country, Jatropha production started in the 1940s but that was at a smaller scale. In 2004, the government deliberately established Jatropha plantations through the National Oil Company of Zimbabwe, with the largest biodiesel plant commissioned in the country in 2007. Challenges experienced in the country concerning the production of Jatropha have remained as lack of policy direction, agronomic expertise, unfavorable prices on the national market, national economic and political shifts, as well as the effects of the poisonous nature of the plant when consumed by livestock (Kuravina *et al*., 2011). Those challenges can also be experienced regarding green hydrogen if it is introduced locally without thinking about its sustainability and some of its adverse impacts on society at large.

5.21. Hydrogen Production, Use and Prospects in Zimbabwe

Zimbabwe's reliance on a mix of hydroelectricity, coal, and biomass is highlighted. The national electricity generation capacity stands at 1,400 MW against a peak demand of 2,400 MW, illustrating a significant deficit that necessitates increased imports and improved demand-side management strategies (Musariri, 2015). This section posits that hydrogen has a better chance of being viable again commercially in Zimbabwe.

5.21.1. Energy Sources Overview

Zimbabwe's energy supply options encompass renewables, yet the proportion of renewables in the energy mix has remained minimal. Approximately 66% of energy originates from biomass, with coal contributing 19% and petroleum products 6% (Get.Invest, 2019). Despite the advancement of solar technology and the potential for hydropower along the Zambezi River, deployment has lagged.

5.21.2. Challenges in the Energy Sector

The energy sector faces considerable challenges, including:

- ***Infrastructure Decay:*** Many coal-fired power plants require upgrades and are prone to breakdowns, leading to extended outages.
- ***Access Disparity:*** While urban electricity access approaches 80%, rural areas languish at around 19%, perpetuating energy inequality (Musariri, 2015).

5.21.3. Renewable Energy Strategies

The establishment of the Rural Electrification Fund (REF) has aimed to electrify public institutions at no cost. The government of Zimbabwe's decision to ban raw lithium exports in January 2023 promotes the local processing of batteries, with the potential to bolster renewable energy technologies (Ngila, 2022).

Before attaining national independence during the 20th century, Zimbabwe had a vibrant commercial industrial sector. Capacity utilisation of the obtaining industry was logged at 100%, and it was keeping pace with world trends as far as mechanisation and standards were concerned. That period involved the scope for hydrogen production and utilisation. Hydrogen-producing companies were BOC Gases and Sable Chemicals from Harare and Kwekwe respectively. Then, BOC produced hydrogen gas for commercial purposes. Its customers included manufacturing and retail chain companies like the then Olivine Industries and Unilever and state companies like the Metrological Services and a utility company (now ZPC installed and commissioned post-Independence). BOC Gases backed the industrial sector with hydrogen, while Sable Chemicals produced for its consumption in support of ammonium nitrate fertiliser production for the national agricultural sector.

The primary producer of hydrogen in Zimbabwe has been Sable Chemical Industries. This is a chemical-producing company that was located in the Midlands Province outside the city of Kwekwe. Sable Chemicals, as Zimbabwe’s sole manufacturer of Ammonium Nitrate, has been using hydrogen since the commissioning of the first plant in 1969, followed by another plant that was commissioned in 1972 (Dimingu, 2015). Companies such as Hwange Colliery were also producing hydrogen through the distillation of coal, although other companies such as ZIMCHEM were extracting hydrogen through destructive distillation.

The Sable Chemicals project was conceived around the 1940s after the government then noted the dependency of the country on agriculture as well as the associated need for self-sufficiency regarding fertiliser production and supplies (Mubonderi, 2012). Sable chemicals produced hydrogen that was used for manufacturing agricultural fertilisers for the country. Zimbabwe heavily relied on its primary industry, which spanned mining and agriculture (Mlambo, 2017 and Kuravina *et al*., 2011). Momentum rose in the 1950s after realising the growing need for nitrogenous fertilisers in the country. In the 1960s, coal gasification was found to be the most feasible technology that could be adopted to meet the objective (Dimingu, 2015).

With the completion of the Kariba Hydropower project, however, a convincing business model for using the electrolysis process was adopted. That was upon realising that oxygen derived from the process would be easily supplied to ZISCO and ZIMASCO, which were both steel-producing companies. Sable Chemicals was then incorporated in 1966, TA Holdings being the major financier, followed by the government and Norsk Hydro, later known as YZ Holdings. Subsequently, the project's groundbreaking ceremony was held in 1967 (Dimingu, 2015).

Pursuits to adopt hydrogen as a renewable energy source in Africa, particularly in Zimbabwe, have been facing constraints against further development and commercialisation. This is the case despite the potential for green hydrogen to assist Africa in meeting its climate, employment, and energy security goals (Grobbelaar and Ngubebana, 2022).

Sable Chemicals has been meeting all national demand for Ammonium Nitrate. Sable Chemical Industries' main product has been ammonium nitrate (Macmillan, 2019 and Dimingu, 2015). The commissioning of the Sable Chemicals plant that converted ammonia to ammonium nitrate in 1969 included 109 tank cars manufactured in Harare at Morewear Industries. Only a few of these vehicles had been imported to support the importation of Ammonium from Mozambique.

The assets commissioned in this section entailed a Nitric Acid Plant, an Ammonium Nitrate Plant, two Boilers, Ammonia Handling Facilities, and a special Ammonia Handling terminal that was installed in Maputo for this factory. At that time, the imported Ammonia was being railed from Maputo, Mozambique. In the third year of operation, the factory reached a production capacity of 170,000 tons of Ammonium Nitrate per year, with 7000 tons of ammonia imported from Maputo monthly (Dimingu, 2015).

The overall plant design capacity of the company was 240 000 mt per annum although between 1969-2000, Sable Chemicals produced 80% to 90% of the country's AN requirement, with the balance imported (Dimingu, 2015). In 1972, the second section of the Sable Chemicals plant was commissioned. It comprised ammonia manufacturing facilities that included the Electrolysis Plant, the Ammonia Plant, and the Air Separation Plant. This led to the fact that 70% of the Ammonia was now produced in situ for the AN Plant, and only 30% continued to be imported from Mozambique.

Commissioning included the oxygen pipeline to ZIMASCO, which was branched to ZISCO along the way. Nitrogen was derived from air separation, while hydrogen was produced through water electrolysis. Lately, the company's ammonia gas requirement has been fulfilled through importation from South Africa (Imasiku, Farirai, Olwoch, and Agbo, 2021 and Macmillan, 2019).

Sable's hydrogen plant got its water supply for electrolysis from the Sebakwe River, which is close by and whose flow is perennial (Dimingu, 2015). The electrolysis plant had 28 cells that produced 23.1kgs/hr (21 000Nm^3). While being the biggest consumer of electricity, it consumed 105 megawatts, which were supplied from the national grid (Africa Energy Portal, 2022; Imasiku, Farirai, Olwoch and Agbo, 2021 and Chance, 2021).

Sable Chemical Industries' hydrogen plant was decommissioned in 2015 due to the high cost of power that was being experienced as well as the erratic supply and shortage of power in the country (Imasiku, Farirai, Olwoch and Agbo, 2021 and Muguwu, 2012). This supports the view that the cost of electricity tariffs is one of the significant impediments to hydrogen production in Zimbabwe, with the high cost of electricity being attributed as the primary contributor, with around 60% of the overall hydrogen production cost (Chance, 2021).

Energy scarcity in Africa is buttressed by the fact that the electricity accessibility rate has been around 56% of its total population, making fuelwood the most dominant source of energy in Zimbabwe, with 90% usage in the countryside (Grobbelaar and Ngubebana, 2022 and United Nations Environment Programme, 2017). In Zimbabwe by 2019, 85.4% of the total urban population had electricity, while in the rural community, only 20.1% had the same (Africa Energy Portal, 2022).

Due to the grid electricity supply challenges, Sable Chemicals has been looking into coal bed methane as the alternative source for powering the electrolysis plant. That was in line with the view that methane gas was identified in Dananda, Lupane, and Binga in Zimbabwe (Dimingu, 2015) although actual methane gas mining was yet to start in any of those identified areas, hence the reliance on ammonia imports from South Africa (Imasiku, Farirai, Olwoch and Agbo, 2021).

Sable Chemical Industries was now relying on ammonia imports from SASOL, a company that is located in South Africa. Sable Chemical Industries, as an alternative to grid electrical power, intended to install a modular solar farm in phases of 50 photovoltaic megawatts per time and with a target of a total capacity of 400 megawatts (Imasiku, Farirai, Olwoch and Agbo, 2021).

In developing the first solar farm, Sable Chemicals collaborated with Tatanga Energy, a fertiliser manufacturer in Tanzania. Forty (40) megawatts generated from the targeted 50 megawatt photovoltaic power generation plant were also expected to contribute to the national grid through the Sherwood Substation, which is around 5km from the solar plant. The project was also expected to see the construction of a 1km 88kv power line by August 2021.

Power shortages in Zimbabwe were being exacerbated by Eskom which was facing critically constrained power generation capacity. Zimbabwe has been relying on additional supplies from the Democratic Republic of Congo, Namibia, Mozambique, South Africa, and Zambia to supplement its local supplies (Africa Energy Portal, 2022).

Besides energy, the chemical industry in Zimbabwe was also faced with several challenges. These challenges entailed outdated technology, a shortage of working capital, limited lines of credit, and erratic water supplies in urban Zimbabwe. Due to these challenges, the adverse spin-off effects that followed were unfair competition from imported products and de-industrialization.

In addition, there has been widespread closure of companies compounded by the adverse effects of sanctions against the country (Zimbabwe Economic Policy Analysis and Research Unit (ZEPARU), n.d.). Further to these aspects, empirical interview data indicates that one of the company representatives prominently highlighted that the shortage of power and the unstable tariff led to uncompetitive business and the ultimate shutdown of the plant in line with the claims by the Africa Energy Portal (2022) and

ZEPARU (n.d.). Also, in 1992, Sable Chemicals faced a water challenge after Sebakwe River was rationed due to drought constraints.

The 2000-2009 high inflationary period saw foreign currency shortages in Zimbabwe and that coincided with the time when most of the ammonia manufacturing equipment was due for heavy maintenance. Lack of finances to buy spare parts and other equipment, therefore, made some sections of the plant inoperable, causing the plant to reach its lowest level of production output in 2009. Retooling that took place after re-dollarisation in 2009 saw production picking up again, but in 2015, the Sable Chemicals plant was taken off the electricity grid by the government (Imasiku, Farirai, Olwoch and Agbo, 2021 and Dimingu, 2015).

5.21.4. Production, Use And Supply Chain Of Hydrogen In Modern Zimbabwe

This section provides an overview of hydrogen production initiatives in Zimbabwe, spotlighting key players such as Sable Chemicals, BOC Gases, the Zimbabwe Meteorological Services, and the Zimbabwe Power Company, specifically the Hwange Power Station, along other noteworthy entities. Hydrogen production in Zimbabwe was historically significant. Sable Chemicals, a primary producer heavily relied on hydrogen for producing ammonium nitrate fertiliser. However, energy costs and infrastructure maintenance challenges led to the eventual decommissioning of their assets in 2015 (Imasiku et al., 2021; Chance, 2021).

5.21.5. H_2 Supply Chain: The case of Sable Chemicals

In Zimbabwe, hydrogen is currently utilised primarily in chemical manufacturing for producing ammonia and for hydrogenation in the food industry. In meteorology, it is also utilised for weather observation through balloons (SAGIM®, 2006). Following an interview with one of the participants, it came out that at Sable Chemical Industries, the produced hydrogen was being fed directly from the production plant into the suction side of the consumer plant such as the ammonia plant, at 30 bar. The produced output was enough to meet the requisite hydrogen demand, leaving no excess for further distribution. As such, the expected 15th pair of the electrolyser was never installed due to limitations of hydrogen use on the consumer’s side. The hydrogen use became limited to feedstock for producing ammonia at Sable Chemical Industries and its subsidiaries, without any other use.

In the same respect, in an interview with one of the key informant interviewees, it came out that Windmill Pvt Limited, which also produced fertilisers in Zimbabwe, used to get ammonia from Sables Chemicals but was now importing it from Russia as a finished product as the company was now focused on producing compound fertilisers only. This claim affirms the view that producing hydrogen in Zimbabwe was no longer competitive businesswise (Africa Energy Portal, 2022 and ZEPARU, n.d.).

In terms of production, the availability of power was initially not an issue as the country had excess hydropower from Kariba. Then, the local industry could not consume all produced electrical energy given the small population that existed. The whole White population was connected during that colonial period. Things changed when the demand for a developed industry grew. The population also grew, with the need for improved access to power by the populace causing the shortage locally and in the whole region (Hasenohrl, 2018). This has broadly happened against the backdrop of limited to no investment in any new generation capacity.

Inflation and increased demand from 1999 to 2015 led to an increase in tariffs, beyond what could be economically viable for continued local production. Sable Chemicals's electrical power used to be subsidised by the government but with time, the government shifted its policy from a negotiated tariff to a commercial tariff. Since that time Sable's business operations became commercially unviable. Like in the case of Namibia, in Zimbabwe, there were many challenges around the funding of hydrogen production and infrastructure (Oertzen, 2021 and Dimingu, 2015).

Hence, the decommissioning of local assets. In any case, hydrogen was naturally viewed as a tricky molecule to store, although lately, there have been safer means for handling and storing the gas. When the Sable Chemicals plant was decommissioned, it was bought by another company in Chile (Dimingu, 2015). That is possible, noting that Chile has a vibrant green hydrogen strategy and a similarly booming green hydrogen gas industry (Correa, Barria, and Maluenda, 2020).

The Davey Bamag Type S 150 E 70 model was used for the Haber process at both ZISCO and ZIMASCO. Bamag is the cell name of the product that was produced by the company Pintssch-Bamag (Gregory, 1972), with patents registered in Germany, France, Brazil, Japan, and the United Kingdom. At ZISCO and ZIMASCO, hydrogen was being supplied through pipes 30km and 15km away from the plant respectively. Oxygen derived through the electrolysis process for hydrogen production failed to meet the required oxygen standards for industrial use, hence, it was disposed of and not stored for any further use. The hydrogen quality was 99.9% and the decline in hydrogen business started around 2010/2011.

The Haber process produced ammonia, which is essential in the production of fertilisers, chemicals, explosives, fibres, plastics, refrigeration, pharmaceuticals, pulp, paper, and cleaning detergents, as well as in mining and metallurgy (Modak, 2011).

5.21.6. H_2 Supply Chain: The Case of BOC Gases

In Zimbabwe, hydrogen is mostly used in the manufacturing, power generation, transport, and retail industries. There it was largely used in metallurgy and for reducing metal oxides. It was also used to prevent oxidation in heat treatment of particular metals and alloys (reducing atmospheres). Hydrogen has also been extensively used in the manufacture of chemicals, plastics, and in petroleum refining. It was further used in the hydrogenation of vegetables, animal oil, and fats. Purified hydrogen was applied in gas chromatography as a detector fuel and in semi-conductor manufacture although the same was viewed as unsuitable for the inflation of balloons (Afrox, 2022).

Given the different hydrogen functions above, BOC Gases' Bamarg hydrogen plant's core business was to supply hydrogen to Olivine Industries and Unilever. These key companies' core business led to the establishment of the hydrogen plant at BOC Gases.

Olivine and Lever Brothers used hydrogen for hydrogenation, particularly for the production of soap and margarine. In the first phase of margarine processing, for example, hydrogenation was done. Hydrogenation is the process whereby the oil is placed inside a chamber and then pressurised using hydrogen to turn the oil into a semi-solid state that resembles custard.

Hydrogen particles would remain within the oil which helped increase the temperature to a point at which it will melt to make the oil less susceptible to contamination through oxidation. The process turns the unsaturated oil fats into trans-fats, oil that is then poured into a large stirring pot, which is heated at $60\mathring{C}$ to $70\mathring{C}$, and then the next phase of the process will follow (ENVIROTECH, 2019).

Due to the cost of hydrogen production in Zimbabwe, these companies were now importing hydrogen or finished manufactured products such as hydrogenated margarine from South Africa. For Unilever and Olivine Industries, which have been part of the Wilmer Group since 2017, hydrogen used to be transported using underground pipes that have been decommissioned. Unilever was about 300m away from BOC gases, while Unilever was about half a kilometer away.

In addition to these two companies, BOC gases also supplied hydrogen to Hwange Power Station. In this case, it used road transport and highly trained personnel for safe handling reasons. Other customers were also buying hydrogen for their fridges as independent customers while upon interrogation, the main uses of the hydrogen bought by some private individuals for personal use could not be established.

BOC gases produced hydrogen mainly through the electrolysis process, particularly reverse osmosis, which is the standard hydrogen production process. The hydrogen produced was taken from the Barmarg to the gas holder, where the space was sealed using water. The hydrogen gas was then compressed into cylinders. The cylinders were pressured with around 1.5 kg of hydrogen at 137 bars.

The still plates used were made of zinc that resisted corrosion. The hydrogen produced was grey, with voltage ranging from a minimum of 191 to a maximum of 192. The minimum Amperage was 3.614 while the maximum Amperage was 3.8. An 11KVA transformer was installed for the plant.

5.21.7. H_2 Supply Chain: Meteorological Services Zimbabwe

At the Zimbabwe Meteorological Services Department in Zimbabwe, it was found that hydrogen gas was used for balloons, which were used for upper air temperature and wind observations as part of weather forecasting. The balloons worked with an omnidirectional antenna that fed the data back. The balloons were launched twice daily, at noon and midnight.

The data derived from the upper air observations was also used in the civil aviation industry. Hydrogen balloons were used because they were viewed as light and flying higher and faster enough to reach the troposphere and deliver the required feedback before they could burst. Radio sounding provided the temperature and wind profiles at about 20-30 fit height in the atmosphere from the ground. Balloons would sustain in space for at least $1^1/_2$ hours and then burst.

The highest the balloons had gone was 30hpa, and usually, at 100hpa, they would burst. These balloons were for 100g and 350g and the 100g was used with the theodolite while the 350g was for the radio. In addition to the Harare hydrogen generating station, another SAGIM® electrolyser was being procured independently by the government for the Bulawayo station. In Zimbabwe, a network of weather stations was using hydrogen balloons. One was responsible for radio sensing while 10 were meant for wind profiling. These got their hydrogen from BOC gases in Zimbabwe.

The Meteorological Services Department was getting hydrogen gas from both BOC gases and in-situ generation. Only one station in Harare, the capital city, was generating hydrogen for itself through water electrolysis (reverse osmosis). The Electrolyser used was an MP8 8 bar that required 12V power to generate 730 Amps for breaking water into hydrogen and oxygen while potassium permanganate was used as the catalyst. Demineralised water was automatically assured into the electrolysis cells (SAGIM®, 2006).

Produced hydrogen gas was stored in tanks and oxygen was disposed of by injecting it into water to leave the water as bubbles. The oxygen purity level was less than 90%. Injection of hydrogen into water ensured that fires were prevented since high concentrations of oxygen were feared as easily leading to fires. The purity level of the generated hydrogen was 99.9%, but that was viewed as also highly risky, and the department was not much concerned with having the highest purity levels as those posed more dangers to users.

Nevertheless, produced hydrogen was analysed permanently, and a sound and luminous warning system blocked production in case of a detected defect (SAGIM®, 2006). The department has been using grid power and the 100kV generator that the department possessed was unable to sustain the load. The thyristor used was worked with AC to split the water. Tank proofing was conducted once per year by putting water into the tanks to detect any leaking points. During that process, safety was taken as a high priority. The material used for constructing the storage tank was noted as internally rubberized steel.

Previously, the Meteorological Services Department did not use the electrolysis process to produce hydrogen. The process they used was, however, even riskier, and the workers were always sustaining hydrogen burns in the process of producing the hydrogen. This hydrogen was produced using Costic potash mixed with aluminum foils from industrial aluminum plant smelters. The use of such waste aluminum dross for hydrogen production through metal-water reaction is common in the engineering field (Kandasamy *et al*., 2023) in addition to the famous coal gasification and water electrolysis.

There are three types of aluminum dross namely white dross, black dross and salt cakes (Singh, Meshram, Gautam and Jain, 2019). These aluminum foils and the caustic potash were mixed in caster iron containers and unfortunately, once the process started, it could not be stopped even when the balloons were filled.

The technology further had a lot of material wastage since the process could not be stopped in between. It was also not good for the natural environment because where the mixing containers were washed disposing of the chemicals, the nearby ecosystem would be completely burnt to the extent that no new plants would grow in those areas.

5.21.8. H_2 Supply Chain: Case of the Zimbabwe Power Company

Hwange Power Station has consistently consumed hydrogen at a rate of 0.8kg/hr. This hydrogen was predominantly produced on-site. Initially, the hydrogen was procured from BOC gases, and the gas was supplied to the power station as per order. Where the hydrogen electrolyser at the power station was down, BOC Gases filled the gap by supplying the requisite hydrogen gas to the power station.

The hydrogen generator brand installed at the power station was the HOGEN® H Series, whose weight ranged from 700kg to 908kg. The recommended breaker ratings were 22kVA, 40kVA, and 58kVA, respectively. Hwange Power Station provides an interesting case in which hydrogen is generated to assist in the generation of electricity from thermal energy. This hydrogen generator's dimensions were 180cm x 80 cm x 180 cm. A further 8 cm was to be added to the height for the installed lifting brackets.

Road transport was used to transport the hydrogen gas from Harare to Hwange, and specially trained individuals handled the hydrogen cylinders. The hydrogen at Hwange Power Station was produced directly for use, and there were no storage facilities for stocking the hydrogen produced at the plant.

5.21.9. Challenges faced by companies in Embracing H_2 in Zimbabwe

With concerted efforts, Zimbabwe can transition to a viable hydrogen economy. Efforts must focus on enhancing local production capabilities, modernising technologies, and developing robust policy frameworks. Investment in research and innovation proves crucial in overcoming the incumbent challenges and capitalise on the opportunities ahead. The Bamag electrolyser design that was installed at both Sable Chemicals and BOC Gases faced several challenges. These plants were old and there were no more spare parts for them on the market as the designs were already phased out from the market by the manufacturers. In addition to sourcing hydrogen from BOC Gases, competitor OEMS of other smaller designs for hydrogen production on the international market directly or indirectly supplied small generators to their customers.

Thus, enabling some companies to install their own smaller electrolysers suiting their company's production demands. That would cut the costs of sourcing the product from BOC Gases. Hence BOC Gases lost a market share except for intermittent buyouts in times of equipment breakdown. Buying their electrolysers was also in response to the local market prices, which were on the high side. This was mainly due to the cost of electricity incurred due to heavy power consumption by the bigger Bamag plants especially where they had to be switched off and restarted again due to reduced demand. A higher level of electricity consumption was experienced when the electrolyser was being started, unlike when it was continually running. Contrarily, South African plants were not being switched off. Instead, they were always kept running, giving South Africa a competitive advantage compared to the Zimbabwean case.

Due to low demand levels of hydrogen on the local market, erratic supplies of electricity, and the high electricity tariff, it became economically unwise to keep the plants running locally. De-industrialisation in Zimbabwe, limited retooling leading to obsolete equipment, and the fact that Zimbabwe was now generally a supermarket rather than a producer, caused the reduced demand for hydrogen on the local market. Other retail-related industries were also now using hydrogenated oils and as a result, there was no more need for buying hydrogen locally.

Likewise, the electrolyser plant at the Meteorological Services Department faced many challenges. One of the challenges was procuring spare parts for the equipment, although SAGIM specialists were deployed to ensure installation, commissioning, and training of engineers and technicians to facilitate local use and unit maintenance.

SAGIM brand, model MP 8 Electrolyser was entirely financed by the World Organisation of Meteorology (WOM) under the Voluntary Cooperation Projects (VCP) in 2006. The country of origin in this instance is France. It was funded through a government-to-government arrangement and in favour of the Global Climate Observing System.

This was done within the framework of the rehabilitation of the station of radio operator survey in Harare. When the French government changed its foreign policy on Zimbabwe, coincidentally, upon the expiration of the contract, the project ended. This also affected the facilitation of the purchase of spare parts, which was part of the expired government-to-government agreement, which had to be handled through the Ministries of foreign affairs of the two countries.

The SAGIM MP 8 Hydrogen generator was produced to inflate meteorology balloons into the upper air stations. The process was taking place in Zimbabwe at the Meteorological Services Department in Belvedere, Harare. Its main advantage was its ability to sustain sudden interruptions and fluctuations in power supplies. The electrolysis cell design further allowed hydrogen generation at 8 bars without a compression device (SAGIM®, 2022).

The installed Bamag hydrogen plant at BOC Gases has been using the asbestos membrane. Some of the storage tanks at the plant were however decommissioned. Degassing was conducted technically using nitrogen. Nitrogen is an innate gas that is good for purging hydrogen. Unlike LP gas which was stored in a liquified form, hydrogen was always stored in a gaseous state. Oxygen was produced at the same site, through fractional distillation. BOC Gases also had manifold cylinder pallets carrying 0.5 kgs (5.9 m^3) of hydrogen gas and there were two gas holders installed and used before the hydrogen was pressured into the cylinders.

5.21.10. Opportunities for the production and use of hydrogen in Zimbabwe

There were limited uses of hydrogen in Zimbabwe because the industry was shrinking. Further, the development of technologies for producing hydrogen gas was not being adopted quickly enough locally. Technologies for producing hydrogen in Zimbabwe were already archaic and incompatible with international technological trends and developments. That gap justifies the potential for research, development, and urgent hydrogen technology deployment on the Zimbabwean market.

Besides that, although hydrogen was not produced in the country at a scale large enough to satisfy the market, there was a need for augmentation, hence its importation in cylinders from South Africa by road, especially for the Hwange Power Station. Thus, the hydrogen market exists. The market still demonstrates the potential for expansion and hydrogen gas commercial. Walk-in customers were buying hydrogen from BOC gases, which justifies the potential of the hydrogen industry in Zimbabwe.

5.21.10.1. H_2 embraceability for household use: Challenges and opportunities in Zimbabwe

Hydrogen is of paramount importance in Zimbabwe. The gap it has to fill is mainly being filled by either imported hydrogen or finished products in cases where hydrogen has to be part of the components of those desired products. During interviews with the key informant interviewees from the companies that were producing and using hydrogen in Zimbabwe, it was noted that the main challenge was electricity since most rural areas did not have it installed in their homes. In addition, there was minimum knowledge of the usability of hydrogen for cooking and heating. The research participants, therefore, agreed broadly that hydrogen remained an excellent panacea for transitioning in line with the green revolution.

Discussions regarding the use of hydrogen for cooking and heating emerged primarily from participant interviews. These insights indicate a growing interest in utilising hydrogen as an energy source for domestic purposes, especially in the context of transitioning to more sustainable energy solutions. Participants highlighted that hydrogen, known for its high energy content and clean burning properties, presents significant potential as a viable alternative to conventional cooking fuels in households, particularly in rural areas where electrical supply is inconsistent.

Fears were rife around safety issues at the rural household level. Most rural households in Zimbabwe had grass-thatched huts. These are the common spaces for household cooking and heating. However, many households now adopt iron sheets for roofing these round huts primarily used as kitchens in rural Zimbabwe. Reference was repeatedly made to these risks of burns while using hydrogen. This mainly came out from some of the organisations which were interviewed. It was observed that most of these hydrogen producers were seized with the operation and maintenance of their plants to satisfy their markets. There was neither mention of internal research nor concerted efforts with research institutions to stimulate technological innovation.

During the key informant interviews with the organisations represented in this study, it was noted that one of the producers was selling hydrogen at US$157.00 per 0.5 kgs. The other company bought the same at US$71.00 per 0.5 kgs. This price difference should be understood from the perspective that the cheaper rate was for a government arm, a regular client with a long-term memorandum of agreement with the supplier. US$157 was the on-counter selling price to the ordinary market.

These prices may be accurate and cost-reflective. The total period of hydrogen use in a household should justify the price since hydrogen stores more concentrated energy than LP gas. That leaves room for further research. Some participants advanced the view that the food prepared using hydrogen could be unconsumable due to the occurrence of hydrogen heat level second to Helium on the scientific table (Davis, 2022). Nonetheless, this also speaks to the need for unique pots when hydrogen is selected for heating and cooking. That is due to its high heat value, which may not be compatible with more metals currently used as utensils and equipment for cooking and heating in the household.

5.21.11. Energy and Renewable Energy Policy and Strategy for Zimbabwe

Zimbabwe has a national energy policy and a renewable energy policy. However, it lacked a hydrogen energy policy, country hydrogen initiative, and sustainable international or private hydrogen initiatives (Imasiku, Farirai, Olwoch, and Agbo, 2021). Also, unlike in Namibia, the National Renewable Energy

Policy does not directly address hydrogen gas, including local requirements for its commercial and industrial uses (Government of Zimbabwe, 2019 and Oertzen, 2021). With regards to policy considerations and frameworks its crucial to understand the contextual definition and difference between come. The commercial sector encompasses businesses and activities that are primarily focused on the sale of goods and services to consumers. This includes retail businesses, service providers, and any organizations that engage in trade with the goal of generating profit. The industrial sector is concerned with the production of goods, often on a larger scale. It includes manufacturing, mining, construction, and other activities that transform raw materials into finished products or products into components.

Interviews with government officials revealed that many companies proposing to enter into the hydrogen production business were targeting the European market. A study was being conducted in the country through the Atlas project, to show the sources and potential for hydrogen production in the country. The results of the study were to lead to a comprehensive national hydrogen strategy for both local and international markets.

In the case of the hydrogen production plants whose production was targeted to the European market, one of the by-products of the process was expected to be electricity. A central national hydrogen plant was earmarked for positioning in the Zambezi Valley through a French company that proposed establishing a solar farm for hydrogen generation in the country.

Through a critical informant interview with the government official, it was further established that Hwange was earmarked for an ammonia plant. Water for producing Hydrogen would be secured from the Zambezi Valley, and electricity for its production was supposed to be supplied from the Hwange Thermal Power Station. This was meant to augment the ammonia production at Sable Chemicals. The required land size for the project was targeted to be 400 000m^2, with the railroad expected to facilitate the transportation of ammonium to Kwekwe, Bulawayo, and Harare.

It should be noted that the proposed solar farm was meant to make hydrogen green instead of the previously planned thermal-powered plant. Borehole water was found to be unviable for the project planned for Hwange because the borehole water in the area was of poor quality. Zambezi River is viewed as offering more stable and good-quality water even during the dry season.

It was unclear whether the government would prefer technology conversion relative to sectors using fossil fuels, although that was expected to be more expensive. This has been giving the government some headaches around reducing costs while climate-proofing the current hydrogen generation process.

The transportation of liquified hydrogen to the European market was expected to happen through the Beira port in Mozambique through shipping in the future. Hydrogen had to be used as an alternative to coking coal, too. Any conversion to hydrogen in the transport sector, among other sectors,, was viewed as only possible when hydrogen is sustainably produced locally. Local production would reduce import costs and extended supply chains, which may hinder safe handling. The shipping of green hydrogen was not viewed as carbon neutral (Oertzen, 2021).

Some barriers to renewable energy uptake were identified in Zimbabwe through stakeholder discussions and reports. These were identified as the absence of renewable energy targets and inadequate studies on the potential for further development of renewable energy technologies. Challenges of high production costs were also identified as affecting the economic viability of hydrogen in Zimbabwe and the inadequate institutional structure dedicated to renewable energy.

Further, there was inadequate financing for the development of renewable energy projects. These projects had high capital costs but Zimbabwe experienced no possible short-term prospects for accessing long-term financing for such projects. The absence of a policy framework to attract foreign direct investment for large-scale investment also prevailed. The lack of incentives for research and development also hindered renewable energy technology development, and concomitantly, local manufacturing of such technology-based products was impacted by limited training and experience of technical personnel (Government of Zimbabwe, 2019). These challenges were persisting in Zimbabwe.

5.22. Chapter Summary

This chapter has unpacked the complexities of hydrogen production and utilisation within Zimbabwe's energy sector. Through the employed SWOT and TOWS analysis, significant insights emerged regarding the pathways for hydrogen as a viable energy source. The historical context, coupled with an understanding of the current challenges and opportunities, reinforces the need for strategic policy interventions and investments to pave the way for a sustainable hydrogen economy in Zimbabwe. The chapter exposes that Zimbabwe is endowed with water that can be used for hydrogen production. In the urban areas, this resource was becoming scarcer, generating a challenge for consistent and reliable hydrogen production in the country. That justifies the significance of locating large-scale hydrogen production plants in the peripheries of cities where sustainable water access is more guaranteed. In addition, it highlights that the price of hydrogen on the local market is still high, although its duration of use at the household level for heating and cooking was still to be verified to enable comparison between hydrogen and LP gas, for example. Energy insecurity is a reality in Zimbabwe, and there is a need for further innovations that can improve and bring new technologies to the stage. The hydrogen used to be transported through pipelines, which were decommissioned, and it is currently moved mainly through road transport. Hydrogen storage tanks referred to as bombs existed at BOC Gases. Nonetheless, hydrogen cylinders were used for transportation from one point to another. In ending, it has to be noted that the hydrogen production industry has dwindled in Zimbabwe due to obsolete technologies. High electricity consumption patterns in a country where demand is already not being met by the suppliers further contributed to the challenges. Electricity tariffs and deindustrialisation are expected to continue into the short to medium term since the 1990s if deliberate policies for economic growth are not urgently implemented.

CHAPTER SIX

6.1. ENERGY USE PATTERNS AND DYNAMICS IN MUKARATIGWA VILLAGE

Chapter Six presents a detailed ethnographic examination of energy consumption patterns and dynamics in Mukaratigwa Village in the Shurugwi District of Zimbabwe. Drawing on qualitative data collected through field research, this chapter underscores the intricate interplay between the village's energy practices and the broader socio-economic and environmental challenges the people in Mukaratigwa village face. It explores key themes such as the prevalent dependence on traditional energy sources like firewood, compounded by a persistent energy crisis driven by climate change and infrastructural deficits. The chapter elucidates local governance frameworks, cultural traditions, economic limitations, and their ramifications for community attitudes toward energy resources, especially concerning the emerging dialogue surrounding hydrogen as a viable energy alternative. By providing in-depth narratives of household energy practices, the research expounds on the expectations and realities of energy accessibility in the village, prompting critical considerations regarding sustainability, agency, and the implications for future energy transitions. Ultimately, the local experiences of Mukaratigwa residents contribute to the broader global discourse on innovative hydrogen and equitable energy policies amidst escalating climate challenges.

6.2. Introduction

This chapter utilises an ethnographic framework to explore the energy dynamics within a rural context, Mukaratigwa Village in Shurugwi District, Zimbabwe. Ethnographic methods outlined by Eriksson and Kovalainen (2008) facilitate a deeper understanding of community interactions with energy resources, thus providing rich qualitative insights. As posited by Smith (2017), employing ethnographic approaches to assess community interactions with energy resources and material culture enhances comprehension of the complex relationship between energy and society, especially in the context of rural livelihoods.

The current political economy of energy in Zimbabwe is characterized by acute challenges, including frequent power outages, chronic load shedding, and climate-induced droughts, which have led to diminished hydropower outputs from key sources like the Kariba Dam. This crisis is exacerbated by outdated equipment, which causes breakdowns and prolonged maintenance delays. The decline in water levels at Kariba Dam, Zimbabwe's primary hydropower source, indicates the climate upheaval that has disrupted energy availability. Despite these challenges, there has been limited emphasis on fostering innovative solutions to the energy crisis.

As the local energy situation evolves, several critical questions concerning the sustainability of energy sources, particularly hydropower and thermal energy arise. For instance, questions such as: How have residents of Mukaratigwa responded to the ongoing energy crisis? What implications does this crisis hold at the community level? How do energy usage patterns vary within the village? What power dynamics influence these patterns? Importantly, can hydrogen serve as a sustainable energy source within this context? This chapter aims to address these inquiries comprehensively.

Guided by a prototype electrolyser design specifically designed to sustain a rural village and using a tailored questionnaire developed for the study, the research initially aimed for broader geographical coverage. However, logistical constraints necessitated a focused case study on Mukaratigwa Village, where pressing energy needs were evident. The insights gleaned from this research are crucial for framing a response to climate change and contribute significantly to the dialogue surrounding hydrogen utilisation and its feasibility as a sustainable energy option.

For this chapter, the data was analysed manually using both SPSS and manually. It also serves as a baseline study of the community on the introduction of hydrogen production and uses within their territory. At the time of this study, the village comprised ninety-eight (98) households, with families primarily inhabiting land passed down through patriarchal lineage.

6.3. Ethnographic Technique and Data Collection

The ethnographic method utilised in this study involved naturalistic observation and key informant interviews with households in the village, along with structured questionnaires targeting an understanding of prevailing energy use and preferences. The questionnaires were designed to capture households' energy-sourcing patterns, preferences for energy types, and perceptions of hydrogen as an alternative energy source. The questions were formulated based on the need to understand community attitudes and behaviors regarding energy consumption while seeking insights into their familiarity with hydrogen as a potential energy source.

Data recording was conducted using a combination of field notes, audio recordings during interviews, and written responses to structured questionnaires. The collected data was securely stored and later meticulously analysed using thematic analysis to identify recurring patterns and themes. This approach ensured the findings represented the community's broader views and experiences with energy resources. The insights gained from this qualitative inquiry could influence policy considerations for introducing hydrogen as a viable energy resource at the community level.

6.4. Background of the study

Understanding the context of rural communities in response to various stressors, including climate change, necessitates a historical perspective on Zimbabwe's land issues (Mabeza, 2015). The main household energy uses in rural Zimbabwe are cooking, heating, and lighting, as further reflected in this Chapter. Historically, residents of Mukaratigwa Village faced displacement under the Land Apportionment Act of 1931, which reserved fertile land for white farmers while relegating African communities to less productive areas. This history contributes to present-day population pressures and environmental challenges, including deforestation (Elwell, 1985; Mabeza, 2015).

This period of land appropriation began during the initial establishment stage of renewable energy solutions to address agricultural needs, although hydrogen was not part of the discourse during that time. As climate change intensifies, and particularly the realisation of the need to reduce the use of fossil fuel usage, there have been calls for a transition to renewable energy solutions, epitomised by international agreements like the 2015 Paris Agreement, which emphasises limiting global warming to below 2 degrees Celsius, necessitating vast and rapid energy transitions (Sweeney, 2018). The predominant overreliance on oil and gas raises concerns about the feasibility of moving away from fossil fuels amid an increasing frequency of extreme weather events impacting energy dynamics at the micro level, including in Mukaratigwa Village. Gleaning the local understanding of energy thus required a comprehensive examination of these dynamics (Smith, 2017). Exploration of this context is crucial for understanding local perceptions and practices related to energy and hydrogen adoption.

6.5. Governance and Institutions

The dual governance structure (both modern and traditional) facilitates energy management at the local level. Drawing from Figure 6.1, it is evident that, governance influences energy sourcing and community engagement in the potential transitions to hydrogen and other renewable sources. Understanding the governance structures is essential for contextualising energy sourcing in Mukaratigwa. Traditional leadership in Zimbabwe is deeply rooted in ethnic customs, significantly influencing energy decision-making processes at the local level (Chigwata, 2016). Mukaratigwa Village is under Chief Banga and three headmen as further expanded in other sections that follow, with most household-level decisions often resting in the hands of males. This patriarchal nature of the rural social structure affects investment priorities in energy solutions, frequently sidelining the need to address the varied energy needs of the rural family members (Horrell and Krishnan, 2006).

To gain a more nuanced perspective on energy patterns in Mukaratigwa. it was found essential to detail the village's social structure. Several households fall under the authority of a single Village Head. Larger villages may be subdivided, though these subunits may remain under the original traditional leadership, which varies across ethnic groups. Traditional leadership is prominent in rural settings in Zimbabwe (Chigwata, 2016). The subdivision into other villages, however, remains under the charge of the leader appointed by consent of the family whose genealogy forms part of the group entitled to that leadership.

Mukaratigwa Village is divided into two sections (Village A and Village B) to facilitate decentralised local governance. Appointment of village heads comes either from community applications or government assessments based on recorded population sizes. The selection of the person appointed as the village head follows the family customs, traditions, and structure (Chigwata, 2016). While traditional leadership patterns adhere to the Shona tribal frameworks hinged on a patriarchal structure where household energy decisions often rest with male heads, the village dynamics shape investment in energy solutions based on individual priorities, frequently sidelining the energy needs of other family members (Horrell and Krishnan, 2006).

Mukaratigwa village is not an exception in terms of following the Shona tribal and ethnic traditions. It is characterised as a patriarchal society where family decisions are made by the head of the family, who is usually the father in a standard Zimbabwean family setup. The head of the family makes critical decisions for the household, including procurement of the family's energy resources. The developments around energy investment in the village are to a larger extent therefore dependent on the head of the family's priorities, knowledge, and interests. This can have the effect of ignoring the rest of the family's energy needs (Horrell and Krishnan, 2006). Specifically, those gendered challenges that women and girls face in fetching firewood as well as their other energy needs in their role of supporting school children who may not have easy access to ICT devices due to high poverty levels.

In Zimbabwe, local governance encompasses modern and traditional institutions, as illustrated in Figure 6.1. Modern local government comprises urban and rural councils that interface with district administration. In the country, provincial councilors were yet to sit for council business at the time of writing, and since the inception of the institution at the provincial level through the 2013 Constitution, that advanced the national devolution agenda. Chiefs, headmen, and village heads represent traditional structures that retain significant influence in rural communities. A complex web of interrelationships defines these governance layers, especially in light of economic hardships since the early 2000s in Zimbabwe necessitated a diversification of leadership roles within familial lineages (Kawewe, 2000; Mkodzongi and Lawrence, 2019).

Traditional institutions are hierarchically comprised of chiefs, headmen, and village heads. In that respect, chiefs in Zimbabwe have continued to create new villages, entrench their power, and reward their loyal subjects as well as for their traditional political power experiences. This information is critical in that it provides a background of a village in Zimbabwe since the study was anchored on a case study of the Mukaratigwa Village. The challenges faced under economic strain are also critical to understanding the energy landscape.

The prolonged economic challenges witnessed from around 2000 in Zimbabwe were devastating and have added the need to create more headmen among families in lineages of traditional leadership as a window for expanding their livelihoods and to ensure more from among themselves enjoyed the benefits of their family inheritance. The economic challenges were partly due to neo-liberal interventions encapsulated by the Economic Structural Adjustment Programme (ESAP) coupled with the Fast Track Land Reform Programme (Kawewe, 2000 & Mkodzongi and Lawrence, 2019). These economic challenges continued to be experienced in Zimbabwe.

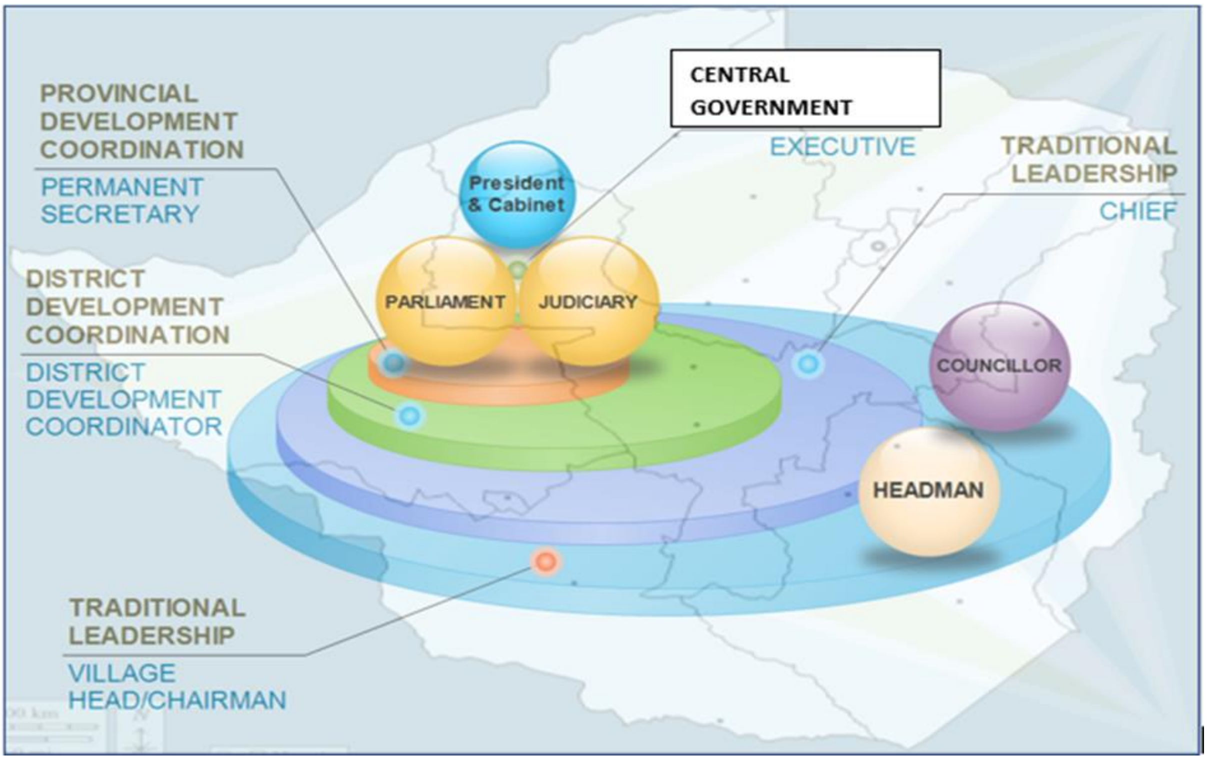


Figure 6.1: Rural governance layout (**Source:** Author's Compilation, 2024).

As illustrated in Fig 6.1 in Zimbabwe, rural governance dovetails two forms of administrative structures which are the modern and traditional institutions. The modern institution groups villages into wards coordinated by a political and elected Councillor who interfaces with district administrative structures. In most cases, urban and rural district administrative councils exist in every district. These are administered by Town Clerks and Chief Executive Officers under the guidance of Mayors and Council Chairpersons respectively. Overall, the entire District is under the purview of the District Development Coordinator (DDC). The DDC coordinates all government functions spurning from traditional, political, civil service, and clergy to communities regardless of their diverse orientations or affiliations related to political and religious persuasions (Centre for Conflict Management and Transformation, 2014).

Villages in rural areas are under the Village Head, whereas those in traditional leadership in Resettlement areas were instead essentially called Village Chairpersons. In Zimbabwe, resettlements are areas where people were relocated from their rural homes (Govo, Dzimiri and Molapo, 2015). Resettlements were born out of the government's Land Reform Programs. These programs sought to decongest overpopulated rural areas under Chieftainships by relocating the people from villages to commercial farms, which predominantly belonged to the minority of the citizens during the colonial era (Dekker, 2015).

Chiefs with vast rural land under their jurisdiction are usually discontented with the leadership system in the Resettlement areas. They were thus, busy replacing Village Chairpersons with people from their lineages and restoring the title of Village Head (Centre for Conflict Management and Transformation, 2014 and Govo, Dzimiri and Molapo, 2015). They argue that their forefathers were dispossessed and forcibly driven out from the affluent commercial areas they previously occupied before the Land Apportionment Act and the subsequent settlement of the colonial masters. Their ancestors' graves continue to lie in the newly settled commercial areas given back to the indigenous people, in an attempt at redressing colonial imbalances and effecting restitution of their land resources (Dekker, 2015 and Geza, 1986).

Village Chairs may have relocated from other chieftainships, incensing the chief, causing the replacement of the serving Village Chair with his preferred Village Head. If there is no relative of the Chief in that resettlement area, a relative of the Chief would be relocated, resettled, and head that particular village to maintain loyalty and allegiance. This helps to preserve the Chief's rule. Moreover, Chiefs rule with the assistance of the Headmen, who are part of their subordinates in the traditional leadership hierarchy. Headmen are traditionally installed and assigned portions of their area of dominion to govern, for ease of reach and control of their subjects while facilitating delegation of powers that ensures mitigating administrative distance and promotion of easy management of a diverse tribal mix. A Headman's influence can spurn over several wards, while at the same time, two or more Headmen's jurisdictions can overlap or converge in one or more wards. This also applies to chiefs whose boundaries can encroach beyond parliamentary constituencies (Centre for Conflict Management and Transformation, 2014).

The DDC, previously known as the District Administrator (*mudzviti*), reports directly to the Provincial Development Coordinator (PDC), who assumed the new title of Provincial Permanent Secretary. This entails more responsibilities following the adoption of the Devolution Agenda by the Government of Zimbabwe. At the helm of each of the 10 provinces is the Provincial Head, called Minister of State for Provincial Affairs and Devolution. This office is a political appointment by the serving President following a general election. These appointee National Assembly or Senate members are elected through universal suffrage or the legally provided quota system. The President also appointed these Ministers of State while being an elected Member of Parliament in compliance with the Constitution of Zimbabwe.

The Devolution Agenda though still under a transitioning stage from a centralised governance system, introduced Provincial Councillors whose regularisation and assumption of office was still a subject for debate by the time of research. Provincial Councillors were sponsored by their political parties and their ability to serve in the Council rested upon electoral votes. The minister, who in this case assumes the role formerly known as the office of governor, reports directly to the President and is part of the Executive.

However, the Minister's Permanent Secretary is appointed by the President, although under the purview of the Chief Secretary to the President and Cabinet with some dotted lines of reporting to the Ministry of Local Government and Public Works (MLGPW). The MLGPW also has a Permanent Secretary who reports to an appointed Cabinet Minister party to the Executive and is appointed by the President in the same manner that the Minister of State is appointed.

Table 6.1. Rural governance layout table

Level/ Office Bearer	**Traditional**	**Local Government**	**Central Government**
District	Chief	Council	District Development Coordinator
Ward	Headman	Councilor	
Village	Village Head		

Many people residing in Mukaratigwa Village while in their active age groups are there mainly because they lost employment during the 2007/8 period. Those vulnerable people who lose employment at those ages largely relocate from the cities to peripheries such as rural or other marginalised areas away from the mainstream economy. Some of these areas have extreme poverty, are remote, are removed from main roads with poor service delivery outcomes, and have severe spatial poverty traps. The conditions were also worsened by weak national macroeconomic conditions, severe droughts, unstable and misaligned exchange rates, cash shortages, and local currency depreciation (Swinkels, 2019). Table 6.2 below shows a summary of the participants' age groups.

Table 6.2. The age ranges of the participants

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	7-16	3	3.1	3.1	3.1
	17-35	39	39.8	39.8	42.9
	36-65	46	46.9	46.9	89.8
	above 65	10	10.2	10.2	100.0
	Total	98	100.0	100.0	

The biggest number of participants belonged to the 36-65 age band (46.9%) followed by the 17-35 age range (39.8%). Those above 65 years of age were 10.2%, and the smallest number of participants (3.1%) comprised those between 7-16 years of age. This data reflects the age ranges of people generally at home in this community depending on the time of the day, day of the week, and season during which the households are visited. The dominant age group (46.9%) confirms that more people in rural Zimbabwe are adults, while (39.8%) were again adults of economically active groups who were not in formal employment.

Children between 7-16 are usually in primary or secondary school unless they are on school holidays. During the summer rainfall season, particularly between October to April, those not working and not attending school were going to the agricultural fields for farming in the morning from around 5:30 am until around 11:00 am. They would then resume from around 3:00 pm to 6:00 pm on the same day except on Sundays when most of the people will be resting while to others, this is usually considered a day of worship. Seasons further have implications on energy consumption for cooking and heating and accessibility patterns in the home. That justifies the need for hydrogen for cooking as those seasons may also mean different levels of burden, especially for the woman and the girl child. Those gender groups were doubling the tasks of farming in the fields with their male counterparts and performing other domestic chores, such as cooking for the family, among others, when they were off the fields.

Key informant interviews conducted to establish what most of the people in the village were engaged in gave insights into how the different age groups spend their time during the day. It was noted that people aged 21 to 35 were usually employed in the nearby mining companies because, in the view of employers, they were still trainable, less rigid, and easy to discipline. Those within the 35-65 age range were either retirees or given up on seeking employment in urban areas.

Those in their late 50s were also mostly unemployable, but they were becoming fewer due to lower life expectancy rates in the country, especially among the poorer people. Those between 7-16 were fewer as they were living with grandparents than their natural parents for different reasons. Most participants in those age groups also accompanied their economically active parents (formally or informally employed) in towns, or they were in boarding schools, hence their limited presence in rural areas.

6.6. Age and Marital Status of Participants

The demographic information collected presents a diverse age distribution among participants. They predominantly comprise individuals aged 36-65 (46.9%), followed by those aged 17-35 (39.8%), with a small percentage of participants above 65 (10.2%), while those aged 7-16 constituted 3.1% of the sample. This demographic breakdown reflects the dynamics of energy sourcing, as adults primarily assume responsibility for procuring household energy.

Examining the marital status reveals that 64.3% of participants were married, while 19.4% were single, 4.1% divorced, and 12.2% widowed. The financial circumstances of households and the nature of marital relationships play pivotal roles in energy sourcing and consumption patterns. Households with married couples tended to share responsibilities, with economic resources influencing energy procurement strategies. In this study, as depicted in Table 6.3 presented below, the least number of participants were between 7-16 years of age, as noted in Table 6.2, and this age group is not legally expected to have married at that stage. Marital status is usually linked to age in the village.

However, there was a case where a few girl children below 18 years of age, and particularly at around 13 years old, were being married. That was attributable to religious persuasions in some families where these kids were raised. These children were sometimes being married by older men due to enticements from illegal gold poachers (Dzimiri, Chikunda and Ingwani, 2017). Where children were married in villages, it also implied that they had to carry the burden of motherhood, unlike their agemates who were still in school. Such girls were therefore in some instances primarily responsible for securing household energy sources for the family. It should also be noted that the Shona society in Zimbabwe is patriarchal mainly and Shurugwi is no exception as stated earlier in this study (Horrell and Krishnan, 2006).

Table 6.3. Marital Status

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Married	63	64.3	64.3	64.3
	Single	19	19.4	19.4	83.7
	Divorced	4	4.1	4.1	87.8
	Widowed	12	12.2	12.2	100.0
	Total	98	100.0	100.0	

Households comprising married couples usually share roles and responsibilities such as securing the requisite household energy source. Where one partner or both partners were employed, the economic capacity of the given household was strengthened. For example, at one of the homesteads that had installed grid power, it was found that the male counterpart was the only one always living in that rural home. He was using grid power for cooking, lighting, and heating. His wife lived outside the village because she was employed in a government department in the Midlands Province’s city, Gweru.

Where men reside in the family home alone, the type of energy source used for cooking may lead to the social and behavioural changes they adopt, which can impact their dietary choice. Some of these men end up with undefined eating and drinking patterns and substandard nutritional uptakes since they may lack the patience to prepare certain meals using firewood. The use of firewood for cooking is also characterised by much-abhorred dirt and black soot, necessitating more discipline to ensure cleanliness and hygiene. Cleaning kitchen utensils is typically a gendered duty in the Mukaratigwa Village, with hardliners considering it a taboo for men. This is synonymous with a common joke that “*Makaranga akaoma*” (simply meaning that the Karanga ethnic group has hardliners).

The Karanga people are found in the southern and central parts of Zimbabwe. That constitutes the Midlands and Masvingo provinces and most of them are descendants and subjects of the Rozvi empire which dominated ancient Zimbabwe between the 17th and the 19th centuries (Mudenge, 1972). They speak the *chi*Karanga, a dialect of the Shona language. Shona is the major vernacular language spoken in most parts of Zimbabwe and under its umbrella are other dialects such as *chi*Zezuru, *chi*Manyika, *chi*Ndau, *chi*Korekore among others (Mudzingwa, 2010). Prolonged deferment of cooking proper meals and using firewood may result in these men seeking extra hands which are mostly from extramarital affairs as well as from nearby female family members. Resultantly, relationships and friendships with family and friends in the neighbourhood may be strained.

That privilege of having installed grid power was usually unavailable to the rural divorced, widowed, and child-headed families whose burden for household energy sourcing rested entirely on the household head except where children had grown up, were out of school, or were on school holidays. In the same respect, households headed by single women were mainly among the poor in Asia and Latin America (Horrell and Krishnan, 2006). However, in the village, in some instances, single women were economically better off in cases where they hailed from wealthy families or where their grown-up children were successful in their various endeavours.

It was further deduced through the key informant interviews that the nature of household energy that a specific homestead accessed was not primarily determined by marital status, but by economic status. Marital status impacted gendered role sharing, and it meant that when children were still young, the tasks were piled on the household head unless they had a helper. In the village, household cultures relative to household energy sourcing nevertheless varied even where the household had both a male and female or a married couple. In the African tradition, there is emphasis on seniority. Those perceived as younger in that context did the chores that required more human energy. In some homes, younger girls and boys (the unmarried) were given the responsibility of fetching firewood for example, even where both mother and father were available in the household.

Some fathers were not as responsible regarding the sourcing of firewood, when compared to mothers especially where the household had both the mother and father. In Africa, women's domestic activities in the household are generally perceived as more (UN Women, 2020). Widows were nevertheless viewed as faring better, especially where the husband might have left some economic assets. In addition, in a study done by Horrell and Krishnan (2006), it was discovered that in rural areas. the size of widow-headed households is usually smaller when compared to those of divorced women. Consequently, divorced women were, to a larger extent, economically worse off when compared to widows.

6.7. Energy Sources and Preferences

The study sought to establish the primary sources of energy utilised in Mukaratigwa for cooking and heating (as presented in Table 6.4). Firewood remains the primary energy source, with 95.9% of households (94 out of 98 users) relying on it. Gas and grid power were lesser-used alternatives, highlighting the community's dependence on traditional energy sources. A small fraction of households (only 3 households) (3%), and one household (1.0%), were using gas and grid power respectively. This reliance on firewood aligns with previous findings across rural Zimbabwe, where accessibility and cost-efficiency drive energy choices.

Interestingly, findings also indicated that, where alternatives are available, there is a significant preference for gas (51.6%) as a cleaner and more accessible option, illustrating a community's inclination toward shifts in energy practices for more environmentally friendly and accessible alternatives to firewood. Knowledge of hydrogen as a potential energy source remains limited, with approximately 48.5% of participants aware of it. This suggests a gap in education and outreach efforts concerning alternative energy solutions. Nonetheless, a community-based approach to education and awareness could support exploration into hydrogen adoption. It is agreed by Maramura *et al.* (2020) that firewood is the primary source of energy for heating and cooking in Zimbabwe as confirmed in this study.

Table 6.4. Energy Sources used by the households

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Firewood	94	95.9	95.9	95.9
	Gas	3	3.1	3.1	99.0
	grid power	1	1.0	1.0	100.0
	Total	98	100.0	100.0	

It is inferred that firewood is one of the primary sources of energy in the village. That was due to its proximity, accessibility, and cost advantages in most parts of rural Zimbabwe. Firewood is the primary source and fallback cooking and heating energy resource, which is why it is primary. Firewood presents many challenges at the household level, unlike where gas and grid power are used. Firewood is provided by Maramura *et al.* (2020) as a source of adverse health impacts among its users. It is claimed that exposure to smoke from firewood doubles the risk of individuals getting lung, mouth, and throat cancer, brain tumours in children, and general depression in the human immune system. Cooking with firewood can be done indoors or outdoors, using open or closed fires. Figure 6.2 below shows a picture of a tin with boiling water on an open fire in the Mukaratigwa village.

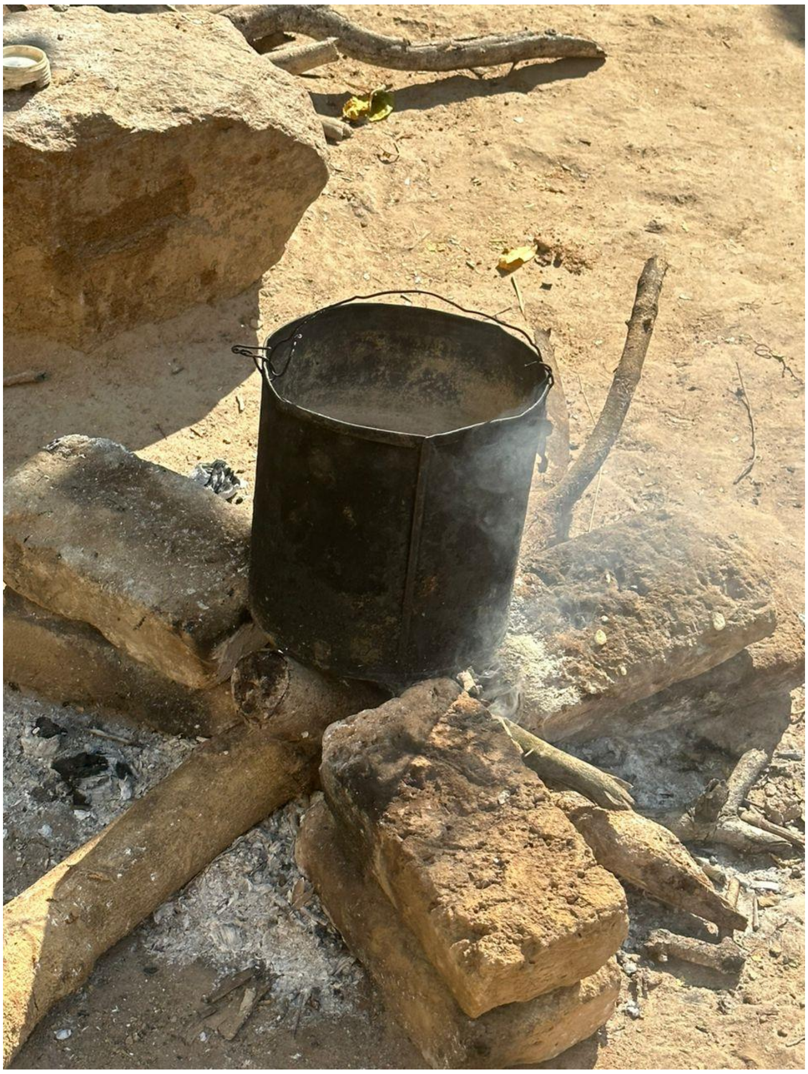


Figure 6.2: Cooking with open fire in Mukaratigwa Village **(Source:** Author's Compilation, 2024).

The primary source of energy was provided as firewood, followed by gas, and lastly, grid power; only 8 households had activated grid power in their homes in this village as noted above, although the other 3 were not on board. The installation resulted from the Government's Rural Electrification Programme which was implemented in Zimbabwe between 2002-2005. The program was structured so that the consumers had to pay part of the transformer purchase value, its transportation cost to the village, and the installation cost. Cooperation towards the whole of village electrification was not garnered in the process.

Young working people from the village initially came together and committed to purchasing the transformer. Nevertheless, only a few of them later came on board when the actual payment for subscriptions was to begin, and with time, only one from among this group ended up buying the transformer. He went on to pay for connections to his home and seven (7) other households. The seven other households happened to be his close relatives, and among them was the one participant who was using electricity as his primary energy source among the few beneficiaries.

6.8. The second source of energy for cooking and heating in the HH

The second energy source used by the village households for heating and cooking broadly comprised firewood, which again had the highest score of 57% (35 participants). Those whose second source was gas came up to 21.3% (13 participants). The total number of participants who used grid power as their second energy source was 3 (4.9%), while those who used solar power were 10 (16.4%), as presented in Figure 6.3. Solar power was used in the village, but no household used it for cooking and heating. The average person in rural areas is faced with many vulnerabilities and grapples with irking a living so much that provisioning for paid energy sources becomes a pie in the sky. In short, high poverty levels hinder the acquisition and maintenance of adequate and sustainable alternative energy infrastructure, while the government lacks the capacity to accord every household access to on and/or off-grid power (Forde, 2020; Winther, 2012).

Those in remote rural settings who barely accessed off-grid power like solar only confined themselves to low-capacity PV systems due to cost constraints. As a result, such low-wattage output installations can only sustain lighting and powering small devices instead of heating and cooking. In the same respect, only 61 participants responded to this question, and the remainder (37) did not respond. That means that the 37 participants relied on firewood alone for heating and cooking. Libertarian-based approaches,, as well as egalitarian models,, are both challenging to attain where. They must be implemented in their pure forms in rural areas. Thus, there is a need for a pragmatic approach that borrows from both models (Karnani, 2010 and Soysa, 2021).

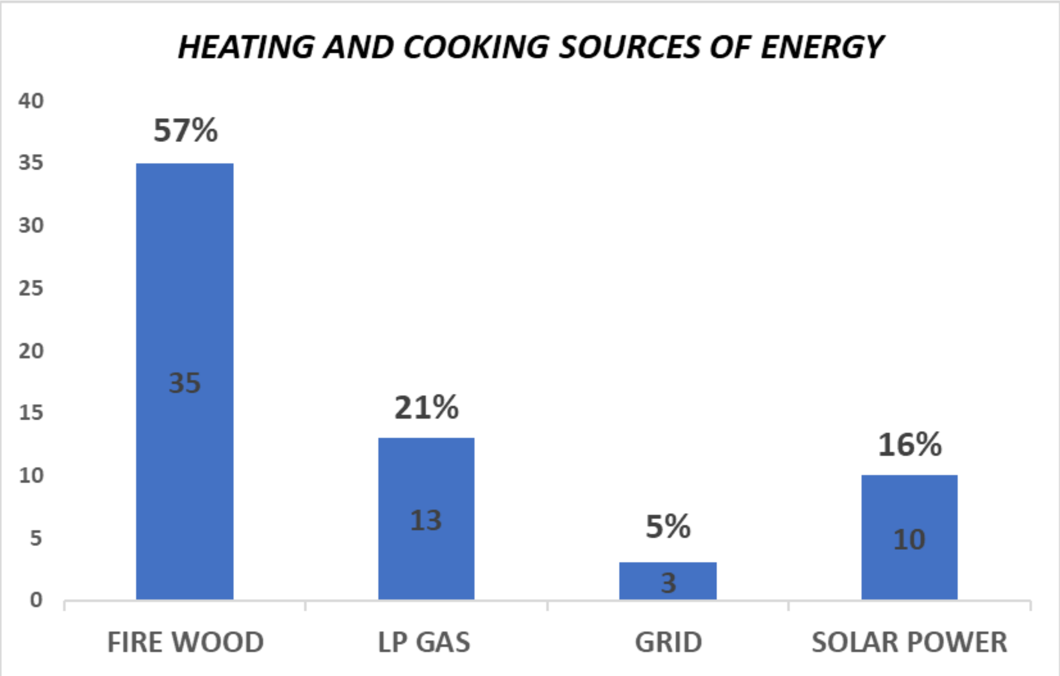


Figure 6.3: Second energy source used for heating and cooking (**Source:** Author's Compilation, 2024).

When the participants were asked to state the type of gas they were using in the village, they said they were using LP gas and bio-gas. Previously, gel was used for heating and cooking, but it did not get much traction because its efficiency level was not pleasing to the rural users. The pie chart presented in Figure 6.4 further presents the type of gas being used in the village.

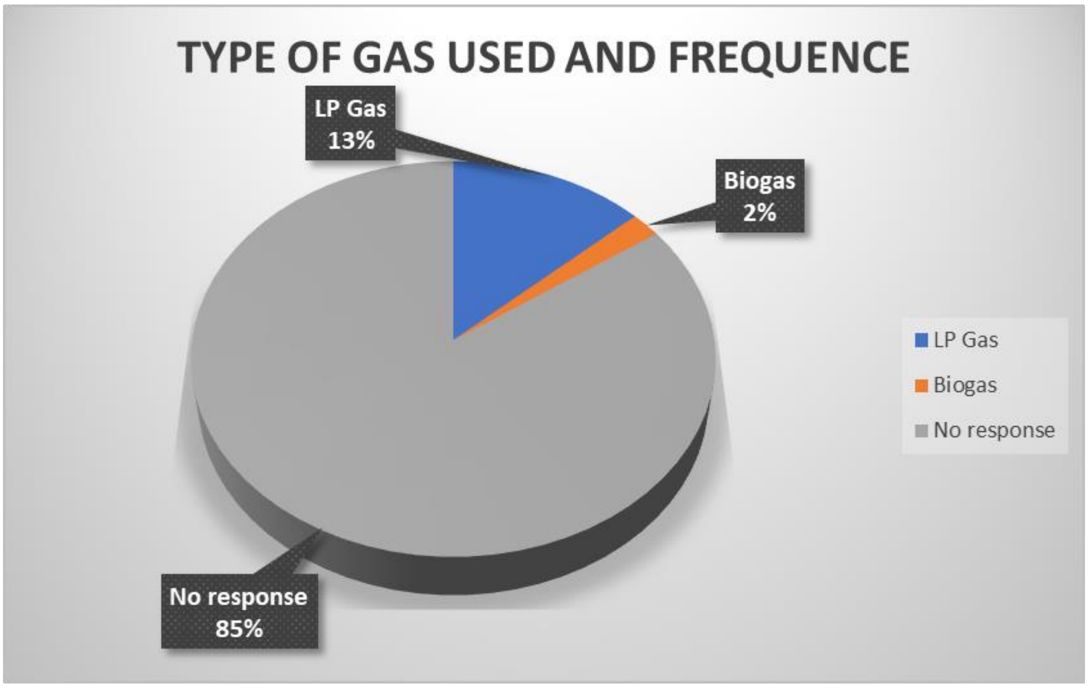


Figure 6.4. The specific type of gas being used in the household (**Source:** Author's Compilation, 2024).

It has to be noted that only 15 participants responded on the type of gas that was being used by the households in the village. Of the 15 participants who responded to this question, 13 (13.3%) used LPG gas, while 2 (2%) used biogas. The more significant number of participants (87.3%) did not respond to this question as it was optional and only meant for those not using gas. It can be noted that 13 participants were using gas. The two participants who indicated that they were using biogas were doing so under the Unki Mines project, which sought to discover the possibilities for using biogas in the village.

Biogas is derived from cattle waste, but most people in the village were not interested in using it because, at the back of their minds, they always remembered that they were preparing food using animal waste. That was bringing discomfort to those eating the food. Biogas use was further at the trial phase; hence, it was not yet effectively used even by those with the facilities installed in their homes. Research also conducted around the embraceability of biogas in rural Zimbabwe exposed that households lacked start-up capital and knowledge of its use. Others had negative attitudes towards it, as mentioned above (Maramura *et al.* 2020).

Implementing biogas as a source of energy faced many challenges among the participants in Mukaratigwa village as has been the case among different users in the country. In the village, they used cow dung, but in some parts of the country, human waste and pig slurry were used. Feeding the biodigester has been the responsibility of the mothers and children regardless of sex. As confirmed in the village, biogas was viewed as gender friendly. The female biogas users affirmed that they were spending less time cooking and sourcing firewood in line with the claim by the Africa for Results Initiative (2016). Whereas they were no longer spending more time looking for firewood, overreliance on cow dung alone put the enjoyment of biogas merits at risk. Drought could cause the death of cattle which could cause the women to again look for cow dung away from their homes for their biodigesters or revert to the use of firewood.

In one of the visits by the researcher to other different areas across the country where biogas was being used, the context dictated who was responsible for feeding the biodigester. A biodigester was fed with human excreta at a school called St David Bonda Mission, a high school in Nyanga in the Eastern highlands. Plumbing was done to enable the diversion of the excreta from the water system toilets that had pre-existed. However, at this school, feedstock was sometimes inadequate to sustainably produce biogas for daily use at that boarding school. St Mary’s Magdalene High School also had its biodigester. This biodigester was not functional due to the unsustainable availability of feedstock. In some instances, the school requested schoolchildren, parents, and the community to bring cow dung from their homes, but that was not helpful as most students would not comply with the directive. The other biodigester at St Patrick’s High School in the Nyanyadzi area, which is in the same province as the mentioned schools, was not functional. In that instance, the system's effectiveness was hampered by the gradient of the connected pipes that were supposed to supply feedstock to the biodigester.

Given the experiences of biogas users in the Mukaratigwa communal area and schools mentioned above, sustainable access to biogas for cooking and heating is sometimes a challenge in Zimbabwe. Juxtaposing the observed experiences to the case of hydrogen production and use, hydrogen may require more technical capacities and funding models to promote its embraceability and sustainability. That poses a challenge to its introduction if there is no strong market or government support system.

6.9. Electric energy uses in the home

The study established that in the village, the households predominantly used electric power for cell phone charging, radio, television, children’s video game powering, ironing, home lighting, and electric sewing machines. In this respect, 35 households (36.5%) needed electric power for cell phone charging only, and 16.7% required the same for powering the television, radio, and video games powering only. Two (2.1%) participants further needed electric power for ironing, while a further 5.2% (5) required it for lighting, and only 2 participants (2.1%) to power their sewing machines. Participants totaling 36 (37.5%) wanted to use electricity for more than one purpose, as illustrated in Figure 6.5 underneath. The data presented in this respect does not imply that the answers given by the participants were mutually exclusive. Participants given an opportunity, would want to use electricity for most of the gadgets noted above. Their responses were nevertheless influenced mainly by the immediate needs that were derived from what they might have possessed or had access to during the time of the research.

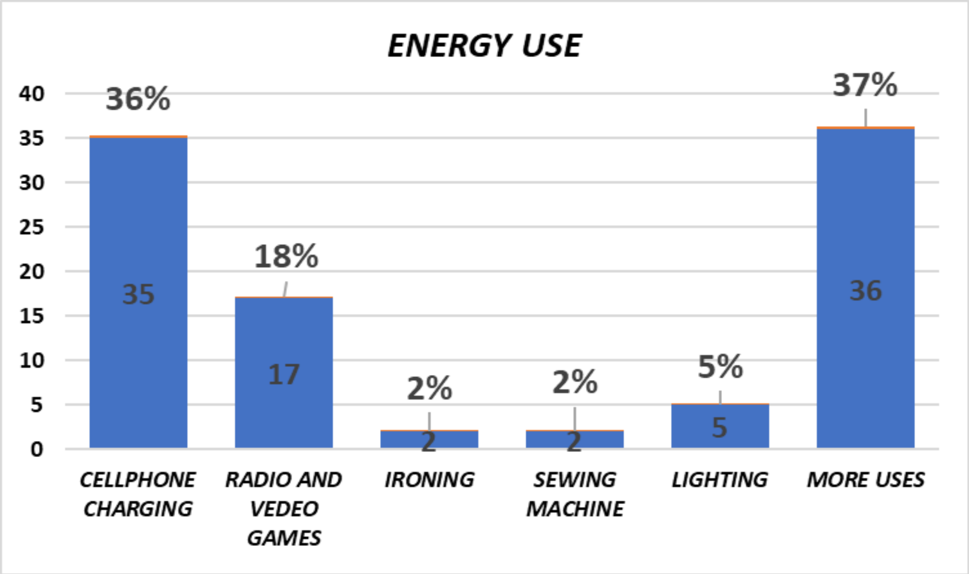


Figure 6.5: Electric energy uses in the home (**Source:** Author's Compilation, 2024).

Of particular note is that some participants indicated that they wanted electric power for their livelihood sustainability in the sense of using sewing machines. Primarily, those who possessed electric sewing machines once worked in the urban areas in Zimbabwe or South Africa, particularly in the clothing industry. When retrenched from employment due to the economic downturn, company scaling downs, or closures, they usually fail to secure either alternative employment or any sustainable form of social protection at exit. Where some had retired from employment on the grounds of old age, they would equally carry their machines to their rural homes, and in those cases, the gadgets were predominantly not used there.

Those with electric irons largely fell in the bracket of those who once lived in urban areas. With regards to electric irons and sewing machines, among others, some households possessed them not by their own choice but through different means. Some end up in possession of the gadgets where a household member who once lived in town died and they got the gadgets as part of the inheritance from the deceased. Others would have children who could have gone to a college or university and acquired the gadgets through sponsorship and on completion of the programs, they reverted home with all belongings. Some were divorced, widowed, or in separation. They would bring these gadgets to their family homes.

Cell phone charging is a very important issue in the village as almost every household has a cell phone. It is also indicative that electricity can be an answer to most of the challenges experienced by the residents in the village. As a result, it was viewed as having more than one use in more than half of the households that took part in the survey. Electric energy is also critical in contemporary rural Zimbabwe. It is important for groundwater pumping, sunflower crushing for oil making, and groundnut processing for peanut butter.

However, there is a general transition in village life in Zimbabwe especially as some lifestyles are shifting as new generations with new orientations in different aspects of life are becoming the "old people" in modern Zimbabwe.

Due to these transitions, the need to also structure the settlement patterns in the village in line with the need to facilitate development, such as energy and power access, becomes very vital. Electric boreholes, oil processing machines, and sawing machines, among other initiatives, are a very good source of livelihood in the rural economy. In some rural areas in Zimbabwe, there are cluster and linear settlement patterns with well-defined road and power networks and water and sewer reticulation services infrastructure, yet that is the opposite in other settings in the country. The aspect of livelihoods must be seriously considered when investing in any form of energy investment in the village. That determines the capacity to sustain access to whatever energy source is to be installed for the community. For sawing machines as a source of livelihood, they can be based in a centralised area in the village, and that also applies to the infrastructure for phone charging. Ironing facilities/points may need multiple clusters, which can be created for the villagers, although that can be difficult given the distance between homesteads in the village.

Mukaratigwa Village has a combination of a linear pattern of settlement and a haphazard settlement pattern, as discussed in detail in Chapter 1. The houses organised in a linear pattern are approximately 100 meters apart and the homes are seated on one-to-three-acre plots each. This has consequences on options for the nature of the power investment options in the village, as these should align with the settlement patterns. Correcting the settlement patterns in the village is not easy especially where the burden of the shift is put on the individual household. It also becomes a key question whether a government-financially assisted rearrangement of settlements is possible in the same context. These aspects are of concern, especially when decisions on the model hydrogen plant to be installed for the Mukaratigwa village and particularly regarding whether a centralised plant or a household-based plant should be the choice.

6.10. Accessing the main source of energy

The study established that 13.4% (13 participants) bought their energy source. One (1) participant did not respond to this question. Sixty-four participants (66%) sourced their energy wholly for free, while 19 (19.6%) were buying and at the same time using accessible energy sources. The majority of the village residents used energy that they sourced for free and for both heating and cooking, as noted in Table 6.5.

Table 6.5. Energy Access options

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Buying	13	13.3	13.4	13.4
	1	1	1.0	1.0	14.4
	for free	64	65.3	66.0	80.4
	buying & free	19	19.4	19.6	100.0
	Total	97	99.0	100.0	
Missing	System	1	1.0		
Total		98	100.0		

Nevertheless, 13.4% were buying their source of energy. That is possible in this village because those using grid power had a prepaid meter installed in the home, and LP gas tanks were refilled at the Chachacha business center. Prepaid metering was introduced in Zimbabwe in the year 2012. Customers buy tokens generated by the Zimbabwe Electricity Transmission and Distribution Company (ZETDC) at any designated selling point which could be in supermarkets and an online platform. These customers are connected to the national grid via low-voltage transmission poles which had to reach their household connection points through a metering unit mounted at a convenient part of the property or house.

Prepaid meters replaced the conventional billing system whereby customers would pay for the electricity consumed every month, after use. These are tamper-proof. In the case of conventional meters, meter readers working for the utility company ZETDC were going out and around to every household to take the meter readings, and the customer would then pay the rates after a bill was shared with them by the utility company. There were challenges associated with this system as many customers defaulted on paying their bills on time despite the interest that failure to pay the bills on time used to attract. Most of these conventional meters were analogue. The prepaid meters were introduced later but already there existed an improved version of the prepaid meters called smart meters in the country. Smart meters have an intelligence unit that detects tampering and can shut down the system in real time. Prepaid meters prevented vandalism of electricity meters, bypassing of metering, and drastically reduced defaulting on electricity payments. Most government buildings and facilities, however, remained without smart meter installations.

On the other hand, lack of or poor income streams and long distances to the LP gas market contribute to its observed low uptake. Chachacha is around 20 km to the North of the Village, while Shurugwi Town is also 40 km to the North, and Zvishavane Town is 60 km to the South. Some of those using firewood were buying it in bulk from the neighbouring farms or from the community paddocks which are largely state land, with consent from the village heads. Others cut trees from their communal farming fields.

Community paddocks are spaces that are communally owned by a village although several villages can access the same leading to the tragedy of the commons stated in Hardin (1968).

These paddocks were neither fenced nor gated. The village head responsible for the area sometimes works with their village and neighbouring villages to maintain the paddocks, especially through clearing invasive species. Trees can be identified for community firewood, inclusive of those invasive species to facilitate organised community access to firewood. Neighbouring villages are included in managing the communal areas as they can also safeguard vegetation from poachers while accessing the firewood when the villages are entitled to harvest the wood. Poachers usually illegally accessed the wood without consent especially when they wanted to burn farm bricks in kilns for their clients. Besides the communal areas, the rural people can cut trees for firewood from their farming lands. In those spaces, they can cut the trees on their own accord, because the trees generally belong to them.

6.11. Responsibility For Sourcing Household Energy

The responsibilities for sourcing household energy were distributed among family members, influenced by traditional gender roles. Notably, fathers were responsible for energy sourcing in 44.8% of the households, while mothers trailed with 22.9%. This reinforces existing gender dynamics, where decision-making around energy demands is male-dominated. Understanding these dynamics is crucial for promoting equitable energy solutions and ensuring that women's energy needs are represented in discussions of energy resource management. Mostly these men who were fetching the firewood were largely unemployed. Most people in the village who were employed were largely employed in government as teachers, nurses, and police officers. Some were employed in the nearby Unki Mine although some were self-employed as small-scale and artisanal gold miners in the same district. In the same respect, 22.9% (22 participants) held that the mother in the household was responsible for securing the source of energy for heating and cooking in the home and these two groups led to a cumulative 66.7%.

Where mothers were sourcing the household energy source, it further implied that in the village, women were mostly unemployed and comparatively more than men in Mukaratigwa village. The family, implying everybody in the household be it a child, father, or mother, was responsible for sourcing the household energy source without putting the overall responsibility on one person. This category scored 9.4% which equals to a total of 9 participants. These households existed in the area and that was more common among the more civilised families including those who belonged to certain religious groups.

In addition, 22 participants (22.9%) noted that children were responsible for sourcing the source of energy for cooking and heating in the village. Two participants failed to complete this question as indicated in Table 6.6. Children who had to source the energy for the household also lost some of their time for education or had such extra burdens after their day in school or during weekends. This mainly affected the girl child as young men mostly have other roles, usually not related to cooking and heating, due to the gendered roles in the households. The roles for young men are herding cattle and goats, among other more labour-intensive jobs in the household. The data above shows that largely, there was a shift in terms of roles in the household as males were becoming more responsible for sourcing the energy source for the household. The main reasons are challenges in accessing some of the energy sources as there is a growing need to travel for longer distances and the growing ability to buy the energy sources on the market. Men usually have the financial resources and, therefore, become more responsible for energy sourcing. Men were becoming more involved in the sourcing of household firewood. That confirms the growing potential for hydrogen embraceability in the village since men were the main decision-makers in patriarchal societies to which Mukaratigwa village belongs.

Table 6.6. Responsibility for sourcing household energy for cooking and heating

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Father	43	43.9	44.8	44.8
	Mother	22	22.4	22.9	67.7
	Family	9	9.2	9.4	77.1
	Children	22	22.4	22.9	100.0
	Total	96	98.0	100.0	
Missing	System	2	2.0		
Total		98	100.0		

The results above show that the mother and children had an equal value in terms of responsibility for sourcing the household energy for cooking and heating although the fathers were more active in this role. Fathers usually used scotch carts drawn by donkeys or cattle to fetch the main household source of energy, firewood. In the same vein, employed fathers were responsible for providing resources for sourcing the energy where LP gas and electricity were concerned.

Usually, people in the village walk long distances to secure the energy source where firewood is concerned. Because children are normally in school, the parents or other people who are in the family such as hired helpers, are the ones who are mostly responsible for this role. Sometimes the youths in the village reciprocate the favours by securing a source of energy for old people and some of their disadvantaged neighbours such as some widows.

Reciprocity is at the heart of the Shona culture. For example, there is a Shona proverb that says, "*kandiro kanoyenda kunobva kamwe"* (one good turn deserves another). For instance, a neighbour in the village had his cattle herded by a neighbouring youth. In turn, the neighbour then extended his assets for use by the of youth's family, assisting them with cattle herding. These assets included the scorch cart and cattle for fetching firewood from a woodland as far as 10 km away from the village.

6.12. Number of times the household sources the main energy source

The highest number of participants, adding up to 29 (30.5%), noted that they sourced their household source of energy twice per month. Nonetheless, 19 participants (20%) sourced their main source of energy for heating and cooking 5 times per month. Eighteen participants (18.9%) indicated that they sourced their household source of energy thrice per month while 17 (17.9%) were sourcing their main energy source once per month. In addition, 11 participants (11.6%) were doing the same four times per month. This data is also presented in Table 6.7 below.

Table 6.7. Times for sourcing household sources of energy per month

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Once	17	17.3	17.9	17.9
	Twice	29	29.6	30.5	48.4
	Thrice	18	18.4	18.9	67.4
	4 times	11	11.2	11.6	78.9
	5 times	19	19.4	20.0	98.9
	6	1	1.0	1.1	100.0
	Total	95	96.9	100.0	
Missing	System	3	3.1		
Total		98	100.0		

Those who mostly had financial capacity sourced their energy source once a month while the majority were that same twice a month, forming a cumulative 48.4%. Only one participant sourced the energy source for cooking and heating more than five times per month and that respondent noted that they were undertaking this task daily and the participant was widowed. A closer analysis shows the level of poverty in the household in the sense that, they would not be able to gather enough energy source to cover longer periods. It can further be attributable to old age where household members would not be able to travel long distances in search of a source of energy such as firewood. In the same respect, that can be coupled with a lack of money to buy firewood from the available markets.

Three participants out of the 98 household participants did not respond to this question. In the village, those who used scotch carts to fetch firewood normally traveled around 10 km to the nearest dense woodland with ready-for-use wood, as already alluded. Near homes and the village, traditional leaders, Ward Development Committees (WADCOs), and Village Development Committees (VIDCOs) were enforcing laws against the illegal cutting of trees to ensure their regrowth and afforestation as part of the ways of adapting to climate change. Enforcement of environmental preservation measures that prohibit the cutting down of trees, is strongly being enforced by the government's Environmental Management Agency. Its presence has given powers to the traditional leadership to assist in environmental management in their local areas of jurisdiction.

Nevertheless, the extent to which efforts towards reforestation, forest regrowth, and afforestation are achieving their objectives in the village remains questionable. The villagers are traveling long distances which are straining certain age groups whose mobility is already retarded by health complications. Further, some children from underprivileged families were continually traveling long distances away from home in search of firewood. That exposes them to dangers of abuses such as rape cases, and time losses where the same time can be spent doing schoolwork than in forests in search of firewood.

This lays bare structural inequalities in society, with implications not only for the generation of the day but if not addressed, the future generations. In the context of Zimbabwe, therefore, achieving Sustainable Development Goal No. 7 is still a challenge (Maramura *et al*., 2020). As a result, access to renewable energy in most of the country's communities is a mirage, while access to firewood itself continues to be made more difficult, exclusionary, and a matter now largely being defined in economic terms and by international conservation regimes.

The country was facing an acute dam water crisis, which has seen the Kariba Dam, the main source of hydroelectricity, drying up. Consequently, hydroelectricity output at the dam had fallen drastically at the time of the fieldwork. At the height of droughts, electricity power generation capacity has been dropping way below 400 megawatts from an installed capacity of 1200 megawatts (Verhoeven, 2022).

6.13. Hours for sourcing main HH heating and cooking source of energy

Noting that firewood has been the main source of household energy for cooking and heating in the village under study as presented in Table 6.8, it is also clear that the highest number of households (33 out of 98) (34%) took over 180 minutes (3 hours) sourcing their main source of energy for heating and cooking. The second largest group (26 participants, which translates to 26.8%) took 120 minutes (2 hours) for the same task, while 18 (18.6%) out of the total participants needed only one hour (60 minutes) to source their main source of energy for cooking and heating. Thirteen (13) participants, which adds up to 13.4%, took 3 hours, while only 7 participants (7.2%) took less than 60 minutes (1 hour) to source their main source of energy for cooking and heating.

Table 6.8. Hours taken to source the main energy source for cooking and heating

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	less than 60min	7	7.1	7.2	7.2
	60 min	18	18.4	18.6	25.8
	120 min	26	26.5	26.8	52.6
	180 min	13	13.3	13.4	66.0
	above 180	33	33.7	34.0	100.0
	Total	97	99.0	100.0	
Missing	System	1	1.0		
Total		98	100.0		

Those households that travel far to get some firewood would also normally take longer to get their source of that energy source for heating and cooking. In addition, those who travel far would get firewood they would use for several days unlike those who can source around their homestead as the quality of the firewood can be poorer. Those who also buy gas travel to refill the tank but that can take an hour or less since Chachacha Business Centre is not too far from the village.

Those who depend on electricity were topping up or *juicing* (in the words of the research participants) their prepaid meters through their cell phones while in their homes. The household size further determines the usability of grid power and gas for heating and cooking as that also translates to costs on the part of the household. Those who use firewood depending on how they source it, would take two to three hours to get it for their households.

6.14. No. of people who are part of the HH present per standard meal

This study reveals that the highest number of households in the village comprised 3-5 people who would always be present for a standard meal. Households in this category were 43 (45.3%). In addition, some households comprised more than 5 people who would be available for a standard meal and these were 41 (41.8%) of the total participants. These two categories together, carried the highest percentage of the participants. Households with one (1) person were 2 (2.1%) while those that were made up of two people who would also partake in a standard meal were 8 (8.4%). In that respect, the Government of Zimbabwe (2017) noted that the average household size in the country was 4.2. In 2012, the Midlands Province had an average household size of 4.5. It was the same in Shurugwi Rural District where the average household size was also 4.5 (Government of Zimbabwe, 2012).

Urban household sizes are usually smaller in Zimbabwe when compared to those in rural areas. Statistics derived from the Mukaratigwa Village are presented in Table 6.9 below. It is important to note that the average Midlands Province household size was 4.5 just as was the case in the Shurugwi District where the average household size was also 4.5. The national average household size decreased in 2017 and it can be acceptable that the results derived in this study, of a 4.0 average household size in Mukaratigwa village, reflect the changes taking place in the household structure in the village.

Table 6.9. Number of people present per standard meal per household

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1 person	2	2.0	2.1	2.1
	2 ppl	8	8.2	8.4	10.5
	3 to 5	43	43.9	45.3	55.8
	above 5	41	41.8	43.2	98.9
	5	1	1.0	1.1	100.0
	Total	95	96.9	100.0	
Missing	System	3	3.1		
Total		98	100.0		

The results above provide a true reflection of the structure of households in the village. Most of these households were comprised of parents and their children or grandparents and their grandchildren. Few old people live without grandchildren in the village. Where that was witnessed, the household usually had fewer people. Some smaller households in the village were a result of working adults living in the urban areas with their children, leaving the grandparents either as singles or as couples, living in the rural areas.

On another note, whereas these families may be comprised of a nucleus household, rural households usually also host relatives who might be living in areas far away from schools. Therefore, they would live with relatives who might want to access better nearby secondary schools, making the household bigger. Other households naturally always have visitors especially where one of the household members holds a leadership position in the community. These positions can include that of the headman, church leader, spirit medium, or any other position of influence, such as that of a Member of Parliament or councilor. Social bonds, networks, and relations in these rural areas are usually still very strong.

6.15. Number of meals prepared per normal day per household

In trying to establish the number of meals that a household has per day, it was found that 53 (54.6%) participants out of 97 participants were taking three meals per day. These three meals are usually taken during the mornings, afternoons, and evenings. These meals are also not wholly prepared when they are about to be served because of the time that may be needed to prepare one of the components of the meal. Part of the meals for the following morning could therefore be prepared soon after supper or while supper is being prepared.

Thirty-four (34) (35.1%) households were having two meals per day. It should be noted that such households have their breakfast midmorning and then the other meal earlier in the evening. Only 6 (6.2%)

were having 4 meals per day. This group usually has children in the home, or some other people with medical conditions with prescribed feeding times. Also, 4 households (4.1%) were having one meal per day. Taking one and two meals per day as a household was also being taken as an adaptive measure. That was common when families faced a lean agricultural season or when they experienced a drought situation in general.

The fact that families can have one meal per day was also witnessed in 2019 when one-tenth of the rural population would go without food for a whole day (Swinkels, 2019). The number of people affected in rural Zimbabwe doubled those in the urban areas although both the rural and urban populations were affected. Grid power interruptions further negatively impacted mining and agricultural production as well as production in the manufacturing industry, leading to more job cuts and less food access in households (Swinkels, 2019).

Schoolchildren from the village were also being fed in schools. They were having breakfast and lunch served with the support from UNICEF and the Ministry of Public Service, Labour and Social Welfare whose finances were allocated through the Parliamentary budget. The program was reestablished in 2016. As a result, sometimes even in households, children were not eating in the morning, as they were being served food at school. This program succeeded because there was a government monitoring mechanism to deal with any challenges that could have been witnessed.

However, there were challenges associated with the centralised procurement system that did not promote local smallholder farmers when compared to more established wholesales. Weak program leadership capacity, in addition, undermined the efficiency and implementation of the oversight mechanisms of the program (Global Child Nutrition Foundation, 2021). Data that summarises the number of meals taken per household in Mukaratigwa Village is presented in Figure 6.6 below.

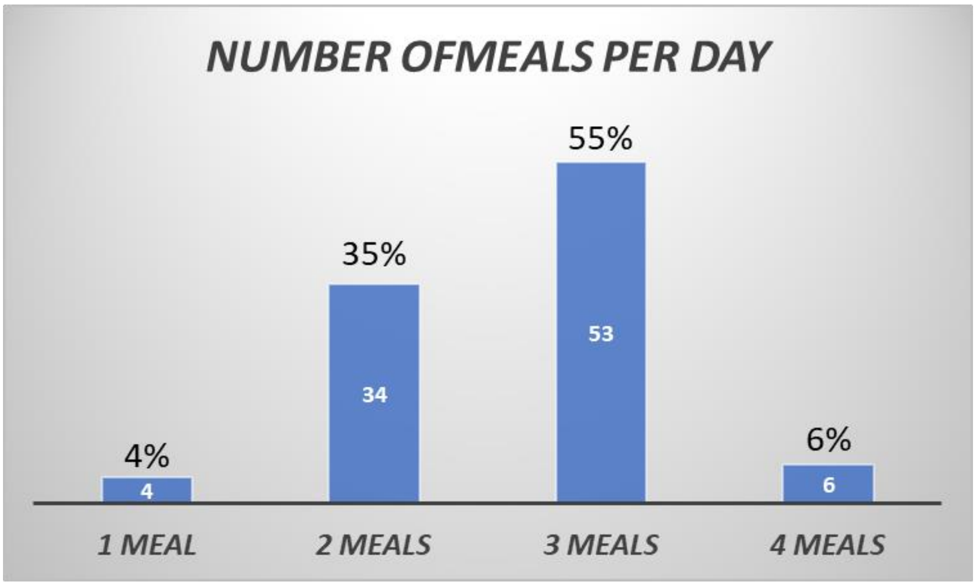


Figure 6.6: Number of meals prepared per normal day per household

The drought adaptive measures are usually a result of livelihood interventions by the government, CSOs, corporations, and other humanitarian development partners. The adaptive measures sometimes also become the households' lifestyle during a drought season or even when the lean season is over. The ingredients required in food preparation depending on the nature of the household in terms of age groups, can further impact the desire to prepare more meals or fewer meals in some households in the village.

6.16. Time taken to cook a standard meal in a household

Participants were asked to state the time taken to prepare a standard meal for their household. It should be noted that 31 (35.2%) participants took 2 hours to prepare a standard meal for a household while 20 (22.7%) took 3 hours to prepare one standard meal for their household. Food preparation would start from zero. Usually, there is no culture of fresh food preservation and fewer semi-processed foods in these villages due to high levels of poverty and lack of refrigeration facilities. Only 16 (18.2%) participants needed one hour to prepare a meal for their household, 13 (14.8%) would take five hours, and 8 (9.1%) would take four hours. It has to be noted that 10 (9%) participants out of the total 98 (100%) participants did not respond to this question making the total number of respondents in this regard 88 (90%) as reflected in Table 6.10 provided below.

Table 6.10: Time taken cooking a standard meal in the household

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	1 hr	16	16.3	18.2	18.2
	2hrs	31	31.6	35.2	53.4
	3hrs	20	20.4	22.7	76.1
	4hrs	8	8.2	9.1	85.2
	5hrs	13	13.3	14.8	100.0
	Total	88	89.8	100.0	
Missing	System	10	10.2		
Total		98	100.0		

The highest number of participants therefore took 2 hours to prepare a meal for their household. The number of people in a household can determine the number of hours taken to prepare the household standard meal. Other households nevertheless prepared two meals only per day. These can also entail meals that may require longer hours of preparation such as beef tripe, beef knuckle bones, cowpeas, sugar beans, and dried groundnuts which may need hours of boiling.

Foods that take many hours of preparation can be left under the attention of younger children. In the meantime, older members of the household may be doing other production roles in the fields, gardens and while they attend to other social and community events. Groundnuts may be taken with tea or without anything else while cowpeas, tripe and knuckle bones are used as relish and taken with *sadza* (staple diet made out of maize meal) or with tea again.

6.17. Source of energy most preferred by the households

The highest number of participating households (49 or 51.6%) noted that they preferred the use of gas. The second highest preferred source of energy is grid power that scored a total of 22 (23.2%) participants. Only 14 (14.7%) and 9 (9.5%) preferred firewood and solar power respectively as presented in Table 6.11 below.

Table 6.11: Most preferred source of energy if that could be availed

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Firewood	14	14.3	14.7	14.7
	Gas	49	50.0	51.6	66.3
	grid power	22	22.4	23.2	89.5
	solar power	9	9.2	9.5	98.9
	6	1	1.0	1.1	100.0
	Total	95	96.9	100.0	
Missing	System	3	3.1		
Total		98	100.0		

These preferences are informed by different persuasions and as could be noted in the table above, three of the participants did not respond to the given energy sources while others would not be prepared to completely leave firewood although they would prefer gas or grid power for heating and cooking. Gas is preferable because it is easily accessible to most households while grid power would need investment that would need more time and resources to be completed. Access to gas is also directly under the control of the user while access to grid power has been impacted negatively through the prevailing power cuts experienced in the country due to loadshedding.

6.18. Knowledge of H_2 gas as an energy source for heating and cooking

The participants were asked whether they had ever heard about hydrogen as a source of energy. Forty-seven (47) (48.5%) were of the view that they had heard about hydrogen as a source of energy for heating and cooking. On the other hand, a total of 50 participants which adds up to 51.5%, held the view that they had never heard about hydrogen as a household source of energy for heating and cooking. Those who did not know hydrogen as a source of energy for heating and cooking were comparably more than those who were aware of the hydrogen gas. Figure 6.7 that follows illustrate the views by the participants.

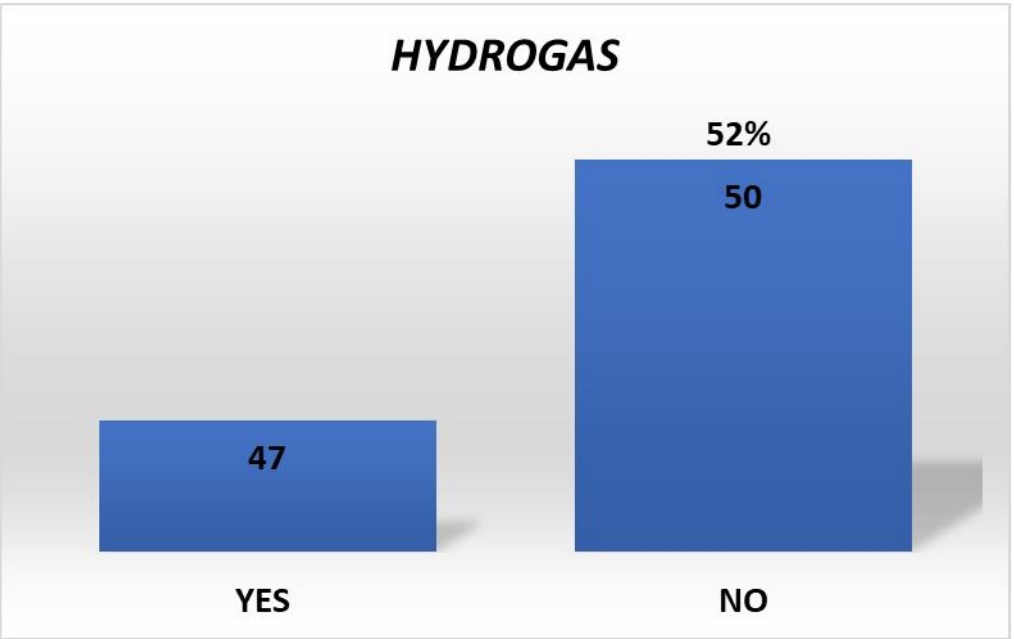


Figure 6.7: Knowledge of hydrogen as a source of energy for heating and cooking

That is possible because in the village, some of the people did not manage to access secondary education. As a result, they did not know about hydrogen gas. Villagers were mostly aware of LP gas. Biogas was only known through pilot projects that were being conducted through the sponsorship of Unki Mine and other non-governmental organisations that were operating in the village. Those organisations assisted the two households that were using biogas as discussed in this chapter above.

6.19. Establishment of how those who knew H_2 first heard about it

In trying to establish how the 50 participants who had heard about hydrogen came to know about it, only 49 out of 50 responded to this question as presented in Table 6.12 below.

Table 6.12: How participants got to know about hydrogen

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	social media	12	12.2	24.5	24.5
	broadcast / print media	8	8.2	16.3	40.8
	community members	15	15.3	30.6	71.4
	School	9	9.2	18.4	89.8
	family members	4	4.1	8.2	98.0
	6	1	1.0	2.0	100.0
	Total	49	50.0	100.0	
Missing	System	49	50.0		
Total		98	100.0		

The highest number of participants (15) leading to a total of 30.6% of the participants, knew about hydrogen through fellow community members. In Zimbabwe, there have been discussions around energy options for the country due to threats of the use of coal and the challenge of accessing grid power due to its high cost. These discussions could have caused even community members to discuss and share information around the same at their level. Twelve (12) of the participants, translating to 24.5%, heard about hydrogen through social media, courtesy of the *infodemic* era. In Zimbabwe, social media includes WhatsApp, Instagram, Facebook, and Twitter and these platforms allow people to access various news which could be local or international. It cannot be denied further that, knowledge about hydrogen could have been influenced through this research since research can naturally equally create awareness on the matter under inquiry.

Those in mining-related WhatsApp groups could have heard about these debates also, as many topics are discussed with participants from across the globe. Secondary schools in Zimbabwe also teach energy issues in line with the appropriate curricula. Therefore, those who attended school up to Form Two level should have heard about hydrogen as an energy source. In Zimbabwe, people usually complete 'O' level studies at 16 years. Only 9 (18.4%) out of 49, had heard about hydrogen in school. Broadcast and print media contributed to the knowledge of hydrogen too as 8 (16.3%) indicated in this study. Those who heard about hydrogen through family members who may have had access through different platforms were 4 (8.2%).

The affluent and those who participated in learning workshops and seminars more with the advent of virtual conferencing platforms like Zoom and Teams were among the more knowledgeable. For instance, the talk about South Africa coming up with a Hydrogen policy in conjunction with climate change mitigation and adaptation strategies might have influenced the spread of such knowledge. This data shows that the community had access to information as an open system, from different sources.

6.20. Chapter Summary

Energy transition in the context of climate change often presupposes energy futures that are deemed "green". More often than not, there is a tendency to valorise fetishized notions of what entails green success. This green success is premised on Western hegemonic narratives. However, the village should be a model of what matters for the marginalised rural communities. The transition to renewable energy will not be a walk in the park. Fieldwork suggested that a transition will be characterised by uncertainty among various socio-economic factors and cultural norms. Consequently, the transition to a renewable energy future in Mukaratigwa Village is complex and fraught with challenges and potential. The ethnographic insights highlighted in this chapter reveal the intricate relationship between energy practices and the broader socio-economic context, underscoring the significance of local governance, cultural norms, and economic realities in shaping energy use patterns. This study teased the overall energy situation in Mukaratigwa Village in Shurugwi District in the Midlands Province. It is imperative to note that there are key issues that have been exposed through the study and these lay a foundation that is important for assessing the possibility of using hydrogen as an energy source in some parts of Africa and particularly in Zimbabwe. As discourse around hydrogen energy develops, policymakers need to engage with these local dynamics and foster innovative solutions that can address the unique needs of rural communities. The findings from this study contribute to broader conversations about energy access, sustainability, and resilience in the face of climate change, paving the way for future research and policy development in Zimbabwe and beyond. Also, there is an infiltration of knowledge about hydrogen in the village and opportunity for its use exists, although these people have highlighted a high preference for the use of the gas in their homes. It was not clear which gas they preferred most. Generally, they also wanted energy for the charging of their cell phones, powering their radios and televisions, fridges, stoves, sewing machines, and video games for their children. This study offered a basis for establishing the possibility of use of hydrogen gas in Zimbabwe. However, for transition to occur, there is a need for a seismic policy shift. Policies ought to promote innovative solutions to complex problems. The investigation underscores an existing potential for hydrogen adoption, particularly if accompanied by community education and a supportive governance system. Overall, energy transition efforts must engage with local governance structures and cultural contexts to cultivate sustainable energy futures in rural Zimbabwe.

CHAPTER SEVEN

7.1. SUSTAINABLE RENEWABLE ENERGY DEVELOPMENT IN AFRICA: SIDESHOW, POTEMKIN FACADE OR REALITY?

This chapter critically assesses the potential opportunities and challenges associated with the possibility of significant sustainable renewable energy development in Africa, using the case of Zimbabwe. It is the zenith of the preceding thesis chapters and the precursor to Chapter Eight. It situates the overall study into the global debate through voices particularly from the Global South, challenging the status quo with a focus on hydrogen, in a case study framed within the broader context of the global energy landscape. This chapter, whose ideas are a conglomeration of the other chapters in this study, confirms that the sustainable development arena is largely binary. It comprises the two main global divides, influencing the subsequent naratives and actions aligned to the dominant sustainable development views. Chapter Seven is not independent of the other chapters. Rather, it is realistically informed by the findings from all initial chapters. It further presents a rigorous critical analysis of findings contained in the various chapters, laying a foundation for the recommendations and conclusions presented in the next chapter. A critical evaluation of existing capacity to innovate and integrate renewable energy sources into available infrastructure towards a resilient national energy network is also offered. Prevailing behavioural patterns and systemic gaps contributing to the conception or misconception of renewable energy reality depend on one's orientation. The Chapter uncovers why renewable energy initiatives are often perceived as sideshows or Potemkin façades rather than meaningful progressive initiatives in the Global South.

Summarily, the study posits that the narrative surrounding sustainable development (SD) has evolved to an extent that recently, it is arguably viewed as a promising route to poverty alleviation and ecological restoration. Nevertheless, there are notable trends of regression in the level of commitment towards implementing several SDGs, prompting questions about the possible tangible impacts of these frameworks, particularly in rural contexts in Zimbabwe. Questions raised include whether the nation's adoption of renewable energy is a genuine endeavour toward sustainable development or merely a performative gesture to meet international expectations regarding greenhouse gas emissions. Furthermore, this study situates Zimbabwe's energy landscape amid geopolitical shifts, market dynamics, and environmental crises provoked by global conflicts, while examining how global economic structures influence energy security and access in rural communities. With significant wind and solar resources remaining largely untapped globally, the study critiques Zimbabwe's policy framework, for its inefficacy and investigates whether renewables can engender real change in the country's energy landscape. Accordingly, the Chapter adequately illuminates the debate on whether Zimbabwe's renewable energy development offers a genuine opportunity for transformation or merely serves as an illusory façade, drawing lessons from the broader context and applying them locally.

7.2. Introduction

The chapter is a discursive amalgam of the global hydrogen issues covered in this thesis and their linkage to the Zimbabwean context, in trying to establish the possibilities for using hydrogen as an energy innovation and accessibility solution for sustainable development in Africa. The study exposes a generally weak support system for improving capacity for innovation and development of a sustainable national renewable energy network for enhancing modern and traditional power supply mechanisms in the Global South. Further, it discloses critical behavioral patterns and systemic gaps in the current discourse on renewable energy oscillating between performance illusions and gains that are largely unsustainable, especially in poorer countries. Thus, the ensuing renewable energy discourse vacillates between sideshows, Potemkin façades, and realities that undermine any meaningful implementation of a sustainable energy development roadmap. As a mitigatory measure to this challenge, the Global South should formulate and implement tailor-made, adaptable, broadly aligned, and sustainable development solutions, learning from domains already endorsing and significantly investing in greener technologies (Friedman and Gostin, 2022).

7.3. Historical and Political Context of Energy in Zimbabwe

The historical and political landscape in the country was integrated to examine the energy landscape in Zimbabwe, cognisant that the national socio-economic environment impacts hydrogen technology development locally. The country has experienced profound shifts in governance structures, resource management, and socio-economic dynamics that have had significant impacts on energy development. Historical injustices related to land and resource allocation, alongside the enduring legacies of colonialism, continue to shape Zimbabwe's approach to sustainable energy policy and practice.

Zimbabwe's National Renewable Energy Policy of 2019 articulates a clear vision for energy access, yet implementation remains stifled by structural and circumstantial barriers. Global disparities in stakeholder engagement and wealth distribution are compounded by global political architecture and political instability that render many development and business initiatives ineffectual. This chapter posits that hydrogen presents not just a technological opportunity but a political one, necessitating the reformulation of engagement solutions that prioritise local community involvement and participatory structures in the energy governance framework.

7.4. Barriers and Enablers for Sustainable Hydrogen Innovations

The study exposes that the potential for hydrogen as a sustainable energy source has not been fully realised in Zimbabwe due to significant barriers such as inadequate infrastructure, high operational costs, and a policy framework that has often failed to align with global developments, which should unlock additional support for addressing local needs. In addition, the entrenched dominance of fossil fuels further complicates efforts to transition toward greener energy solutions.

7.5. Technological Development

While Zimbabwe possesses substantial renewable energy resources, the lack of investment in local technological innovation continues to hinder progress. Therefore, breaking away from dependency on external suppliers is crucial for fostering homegrown solutions that leverage local capabilities and address specific community needs. Stakeholders must promote partnerships between local innovators and international entities, to facilitate technology transfer and adaptation and to ensure that Africa, and more specifically Zimbabweans, are not merely consumers but active participants in the renewable energy landscape.

7.6. Policy Reforms for Hydrogen

Current policy frameworks in the country focus on abstract aspirations rather than concrete strategies. For hydrogen to be integrated into Zimbabwe's energy mix effectively, policies must be actionable, addressing regulatory, financial, and infrastructural strategies. Decision-makers also have to prioritise the development of robust procurement mechanisms and financing models that enhance investment attractiveness in hydrogen projects. That background, as exposed in preceding chapters, contributes to the debate on the realities of achieving the green hydrogen agenda in Zimbabwe.

7.7. Discussion of The Overall Study

The study is suggestive that while Sustainable Development (SD) was initially embraced with enthusiasm, emerging trends reveal troubling regression in the efforts towards achieving many of the Sustainable Development Goals (United Nations Development Programmes, 2022; Bendell, 2022). The SD concept was heralded as a transformative approach but in reality, the actual ethos for sustainable development is now faced with heightened scrutiny regarding its tangible impact and effectiveness. SD has become an acceptable catchphrase in the development parlance and continues to be depicted as having the potential to alleviate poverty (Friedman and Gostin, 2022; Mensah and Casadevall, 2019 and Lippert, 2004). When it came on the scene, it did so with much pomp and fanfare; however, evidence shows that humanity is moving backward in fulfilling many of the Sustainable Development Goals (United Nations Development Programmes, 2022 and Bendell, 2022).

The “knight in shining armor” that was originally presented with much fanfare within the discourse of development (Lippert, 2004), is now faced with realities that expose ongoing challenges of aligning the SDGs with the local contexts in which they are applied, particularly in Zimbabwe's energy sector. Artistically, it was welcomed with flowery language such as ‘All hail the new kid on the block’ which took the developmental discourse by storm; nonetheless, Sustainable Development equally has a chequered history and a contested future (Lippert, 2004) in the clean energy context as the discussions in Chapters 1 – 6 of this Thesis depicts.

The SDGs as a framework, despite reinvigorating the sustainable development paradigm (United Nations, 2022; Friedman and Gostin, 2022), is seen through this research as long on rhetoric and aspirations, and short on pragmatic relevance to the real-world policy and programming solutions to the broader energy challenges typically encountered in rural communities in the Global South (Slay, 2018). Unfortunately, many initiatives are implemented ineffectively, yielding minimal, if any meaningful impact (Manjengwa, 2007). Within Zimbabwe's energy context, the existence of strategic global and national frameworks routinely suffers from frequent implementation failures. Notably, the SDGs rubric has reinvigorated the sustainable development paradigm (United Nations, 2022; Friedman and Gostin, 2022), but critiques from a teleological ethical viewpoint underline a disconnect between aspirations and the on-ground realities faced by the majority of Global South rurales (Slay, 2018). These concerns extend to Zimbabwe's energy context, where despite the existence of strategic frameworks, implementation has frequently lagged. Concerning hydrogen though, the national policy framework has even remained silent.

An analysis carried out in this study leads to contemplation as to whether sustainable energy development efforts in Zimbabwe constitute a mere sideshow or a Potemkin façade, and doubts if government initiatives represent genuine efforts to reduce greenhouse gas emissions or simply serve as symbolic gestures, especially concerning green hydrogen. As the rhetoric surrounding sustainable energy expands, particularly amid the backdrop of international pressure, it is essential to discern whether this reflects impactful action or superficial compliance, which is the core idea that anchors this study.

Within this framework, it was necessary to consider the geopolitical limitations, policy shifts, and broader energy dynamics that challenge access to secure, affordable, and long-term energy in Zimbabwe, especially in the face of rising inflation, resource shortages, and geopolitical conflicts impacting energy provision and transition. The global shift from fossil fuels toward cleaner energy alternatives like hydrogen reflects current trends (Lehmann, 2017). Nonetheless, the regression of electricity access metrics across Africa raises alarm, as many people continue without access to clean energy (The World Bank, 2022). The study illuminates the global negative factors against achieving the SD agenda and Zimbabwe faces similar challenges, including rising inflation, shortage of some cleaner resources and capacity to exploit existing ones, and geopolitical conflicts affecting energy provision. In the face of such disruptions, there exists a critical opportunity to embrace hydrogen innovations and promote green technologies. This thesis evaluates the viability of leveraging existing infrastructure, the innovation landscape, and socio-political contexts to advance sustainable energy solutions anchored in hydrogen in the Global South, and more specifically in Zimbabwe, exposing more retardation than advancement.

This study thus, as a result, grapples with the rhetoric of sustainable energy development in Zimbabwe. Is renewable energy development in Zimbabwe a sideshow, a Potemkin façade, or facts on the ground reveal high impact? It reveals low impact. In other words, the study exposes that sustainable energy development in Zimbabwe is a 'feel-good exercise' by the authorities so the country is also seen to be playing a role in reducing the emission of greenhouse gases (GHGs). The study further asserts that like everywhere else in the international development space, sustainable development remains a sung hero.

But does this sung heroism translate into high impact on the ground as already alluded to? The reality presented in this thesis, to a larger extent, does not affirm the above claim.

Against the backdrop of the SDGs, the study highlighted that there are also energy-related geopolitical limitations, shifts, and policy challenges when it comes to ensuring secure, affordable, and long-term energy access. Energy systems are shifting away from fossil fuels such as oil and gas which exacerbate the carbon footprint toward cleaner energy sources such as hydrogen and related materials (Lehmann, 2017). Buttressing the limitations and challenges of achieving the SDGs regarding energy, the study notes that access in Africa is reversing and there is an increase in the number of people without access to electricity besides a decline that has been witnessed until 2020. The risk perception on infrastructure development loans to the developing world is rising, which makes the cost of loans more expensive for developing countries to access them for innovative energy and technology investment (The World Bank, 2022). This, therefore, presents another challenge.

On the other hand, traditional oil and gas exporters were likely to lose leverage in the future as new primary suppliers emerged. This has geopolitical ramifications playing out in real-time (Lehmann, 2017), placing many countries, including Zimbabwe, at stake today and in the future. Climate commitments, technological advancements, and adaptive industrial strategies drive the transitions. That is the new direction because the energy world is transitioning and making strides in innovations aimed at reversing negative climate impacts that continue to inflict on the planet yet the Global South is largely being left behind.

Supply chain constraints are a common challenge and often are the roadblock impeding acceleration towards the energy transition. The Russian invasion of Ukraine frustrated the energy supply domination status quo in Europe to the extent that other parts of the world felt the impact (Darvas and Martins, 2022). That resulted in skyrocketing prices among other ripple effects. This presents an opportunity for interventions inclined toward supporting the greening of low-cost hydrogen-based renewable energy producers and suppliers in the Global South (Grajewski, 2022). Thus, supporting the need for scaling down the market price of hydrogen gas through continuous research as highlighted in Chapters 3, 4, and 5. Trends of rising energy prices are particularly common where oil and gas have been required for winter heating, core industrial processes, and for balancing intermittent renewable energy sources.

Eventually, through this study, the world is challenged to provide energy alternatives that meet the dramatically increased demand and energy insecurity realisation created by the gap in supplies of oil and gas. Zimbabwe is not excepted from experiencing the negative impacts of the Russo-Ukrainian War. These challenges spanned from agricultural inputs, food prices, and food consumption to fuel and migration flows (World Food Programme, 2022).

The eventualities of experienced energy shocks globally and in Zimbabwe necessitate the scaling-up of hydrogen innovations, production, local market penetration, and promotion of such green technologies. Facilitation for the embracement of the technologies questions the usability of existing transportation routes and infrastructure for the new energy sources, as discussed in the case study of the Mukaratigwa Village in Chapter 6. In Africa, those issues are a challenge besides the fact that hydrogen is also needed for ammonia, among other applications highlighted in Chapter 5 in the case of Zimbabwe's industries. Besides the slow progress in Zimbabwe, other countries, especially in the Global North have already established fiscal greenflation mechanisms to ensure the speeding up of transitions to green fuels and technologies (Airaudo, Pappa and Seoane, 2022).

Zimbabwe, in that respect, has zero-rated import duty on green technologies, including electronic devices such as the solar system. This was done through Statutory Instrument 147 of 2010. The National Energy Policy of 2012 further supported investment in renewable energy, and the same applies to the National Vision 2030 (2018) and the National Renewable Energy Policy of 2019. In the fiscal budget of 2020, Zimbabwe then suspended duty and value-added tax (VAT) on solar and its parts. Today, the country has Statutory Instrument 78 of 2021 that is operational and which superseded Statutory Instrument 147 of 2010 by adding more solar-related products, among others, on the zero-rated list. These products encompass charge controllers, batteries, balance of system components, and other solar technologies (KfW Development Bank, 2021). Those efforts indicate the Global South's efforts in the global matrix to achieve sustainable development.

These shifts triggered the rejuvenated massive exploitation of materials for downstream, upstream, and horizontal linkages compensatory to existing energy supply systems. The materials encompass heavy renewables, nuclear, and batteries for electrification. In this rush, there is less socio-economic and political change in the skewed global structure relative to the supply of critical materials and technologies for energy transition, including in the Global South. Most of the products continue to be manufactured in the Global North and India, China, Japan, South Africa, and Brazil, among other countries (Toprani, 2021), as noted in Chapters 2, 3, 4, and 5 that comprise this thesis.

As the Global North seeks critical materials and new partnerships in the Global South, financing for research and development is being received in the Global South, while market penetration continues. Countries in the Global South are warming up to North-South collaboration which has largely been weak, while seeking equity participation and empowerment models in energy investment for enhancement of local innovation for self-help against overdependence on the Global North continues (Lema and Rabellotti, 2023).

The steps taken towards realising such goals create significant stressors that jeopardise the climate and previous development gains. Whereas these interventions are required to ensure a more secure, resilient, and equitable energy system, it is also apparent that achieving one goal may impact other goals either positively or negatively, which is why there are also debates on whether the sustainable development agenda is the ideal approach to development as presented in Chapter 1 in this thesis.

Therefore, there is a need for balance as potential gas suppliers, particularly in Africa, are pressed to exploit their reserves and potentially lock in decades of associated GHG emissions. In response to global energy supply disruptions due to the Russo-Ukraine war, many countries that previously discouraged the exploitation of non-renewable energy were now supporting the expansion of the same (Covert, Greenstone, and Knittel, 2016). Unfortunately, that exposes the self-interested nature of countries party to the sustainable development agenda.

The meeting of the global minds is necessary as a catalyst for piloting and accelerating the traction gained in the development of integrated renewable hydrogen production in African countries. Large tracts of land are relatively affordable in Africa, as noted in Chapters 3 and 6 of this thesis. This resource is complemented by the endowment of abundant renewable and non-renewable resources and critical minerals which are feedstock materials primarily for various industries in more developed countries (The African Capacity Building Foundation, 2017), yet unexploited as argued in Chapters 5 and 6.

The renewed rise in demand for minerals perpetuates inequitable and exploitative practices common between the North and South, promotive of inefficient mineral extraction and industrialisation. High demand emanates from the increased use of critical minerals such as lithium, copper, cobalt, nickel, and rare earths (Altiparmak, 2022 and Department for International Development, 2010). This is on the backdrop of the fact that the world is increasingly relying on China which currently churns out approximately 70% of solar photovoltaic (PV) panels and close to 80% of lithium-ion batteries (Altiparmak, 2022). These realities are also a source of the geopolitics of hydrogen discussed in Chapter 5.

The COP27 platform saw the announcement of a raft of measures incorporating a global multibillion-dollar funding framework to stimulate and sustain cleaner energy development initiatives. Whereas hydrogen potentially plays a vital role in the sustainable development matrix, its downside is the unintended consequences of diverting attention from the more critical developmental needs, especially in the parts of the world where the hydrogen gas itself is currently unfamiliar.

The emphasis is to mend the rift in approaches to tackling energy poverty in Europe and among Low and Lower-middle-income nations in Africa and Asia. A tolerant and united approach factoring echoes from the South’s overarching quest to discuss and surface knowledge and research gaps for accelerating safer, cheaper, and sustainable energy access that saves the world, is necessary (Altiparmak, 2022).

This study argues that sustainable development’s soft underbelly is that, it appears not to generate methods for dismantling the colonisation of the human lifeworld. Its ontological foundations are colonial and premised on forms, flows, and methods collectively producing a somatic system of metabolic unfreedom. More so, as the call for renewable energy gathers momentum, this study asks: Is sustainable development merely rhetoric, or it is supported by reality on the ground? Sustainable Development Goal No. 7 aims to "Ensure access to affordable, reliable, sustainable and modern energy for all” which is critical to the *development* of agriculture, business, communications, education etc. (UN, 2015).

According to Zimbabwe’s National Renewable Energy Policy:

> Zimbabwe has vast renewable energy resources like solar, hydro, biomass, and to a limited extent, wind and geothermal that to date have largely remained unexploited. The majority of the population, especially in rural areas, has no access to basic energy services, with the energy supply-demand gap continuing to widen. The Government of Zimbabwe, non-governmental organisations (NGOs), and the private sector have supported the development of renewable energy since the country`s Independence in the year 1980. Several programs have been implemented to promote the adoption of renewable energy technologies such as the National Energy Policy, Sustainable Energy for All (SE4ALL), The National Biogas Programme, Rural Electrification (using solar mini-grids), Nationally Determined Contributions (NDCs), Renewables Readiness Assessment (RRA), and Climate Policy among others (National Renewable Energy Policy, 2019: 4).

Further, the country’s vision on renewable energy is clear: To “provide energy access to all in a sustainable manner by increasing the contribution of renewables in the country's energy mix” (National Renewable Policy, 2019: 19). Such a vision represents the frameworks found in many other parts of the world, especially in the Global South, particularly Africa. Table 7.1 below shows the policy objectives.

Table 7.1. RE policy objectives

Objective Number	Objective
Objective 1	To have a strong institutional and regulatory framework for promoting up-take of RE
Objective 2	To have a robust procurement mechanism framework for the purchase of RE, thereby promoting investment in the sector
Objective 3	To reduce development timelines by addressing the risks, and issues and simplifying the approval process
Objective 4	To improve electrification levels sustainably by promoting off-grid technologies.
Objective 5	To have a robust financing mechanism for funding capital-intensive RE projects
Objective 6	To increase local participation and community involvement in projects generating energy from RE sources
Objective 7	To empower children, youth, and women through skill development workshops, training programs, awareness campaigns, local participation in RE projects and campaigns, well-designed schemes for key areas, better employment opportunities, and others.
Objective 8	To incorporate a comprehensive communication strategy, increase the level of awareness of developers and end users on setting up RE projects, and use benefits of off-grid products and RE equipment respectively
Objective 9	To promote local manufacturing of RE equipment
Objective 10	To support and complement the provisions in the biofuel policy

(**Source:** National Renewable Policy, 2019: 20).

The objectives stated above appear to have remained, to a lesser extent, sustainably implemented in the context of Zimbabwe, where the study was broadly domiciled. Objective 6 on increasing "local participation and community involvement in projects generating energy from RE sources" appears to be rhetoric as shown by fieldwork data that is presented in the preceding chapters. The participants advanced no such consultations were ever conducted by the responsible authorities. Jolly (2011) weighs in on the importance of participatory approaches in sustainable development by stating that:

> Participatory approaches require decentralisation and democracy – to empower poor people and others who are excluded and to give them real choices over their lives… It also means changes in approaches, operationally and intellectually. People-focused methodologies and approaches need to replace dominant paradigms of top-down

> planning, top-down management and top-down economics. In their place must come approaches and methodologies that recognise the wisdom and experience of people and give them the opportunity and capabilities to make their own choices (Jolly, 2011:30).

Top-down approaches might have the unfortunate effect of reproducing inequalities as such approaches mostly benefit the elite. Development objectives should be tailor-made to embrace the peculiarities of local places. In the same respect Zimbabwe provisioned for the devolution of powers to local-level institutions to enhance both local-level participation and adaptation of development efforts to appropriate local-level contexts. In that respect, Nyikadzino and Vyas-Doorgapersad (2022) advanced that implementation of devolution has been a matter of political contestation in Zimbabwe and considering on-grid energy supply, it is largely centralised for the whole country. Hydrogen stands a better chance as an off-grid alternative energy source that resonates well with the sustainable development agenda, including in Zimbabwe, besides its other potential limitations in some rural communities.

Objective 8 calls on incorporating "comprehensive communication strategies and increase of the level of awareness of developers and end users on setting up RE projects, and benefits of off-grid products and RE equipment respectively" (National Renewable Energy Policy, 2019: 4). Interestingly, Forde (2020) makes observations about the terms off-grid and on-grid from a cultural perspective. In that claim, being off-grid in the UK context was a lifestyle choice in contrast to Mukaratigwa Village where being off-grid was stigmatised. In Zimbabwe on-grid disrupted and extended daily life while on-grid beneficiaries made up the highest number of electricity consumers (ibid).

In Mukaratigwa Village, being on-grid enhanced one's social status. It is remarkable. Villagers with access to electricity are referred to locally as *mbinga* (effluent). Those who are off the grid are seen as not 'having arrived' and that is, they are socially regarded as living from hand to mouth.

Objective 3 of the renewable energy policy targets the reduction of development timelines by addressing the risks and issues and simplifying approval processes. Whereas that objective embeds aspects of efficiency and effectiveness, risk remains a challenge in the supply of some renewable energy sources. The development of innovative technologies is supposed to be facilitated through research and development programs by a combination of government, business, and academic or research institutions. Such collaboration has been weak in Zimbabwe, while risk remains high. Some investors in the sector have also been discouraged due to the challenge of balancing land rights, water rights, and the need to install energy generators in some smaller dams across the country. The processes have also not been clearly defined; hence, there was room for discrimination in the application approval process by the different investors, with negative implications on the renewable energy development in the country.

Objective 5 of the National Renewable Energy Policy spells out the need for a robust procurement mechanism/framework for promoting investment in the sector, which is equally difficult to fulfill with expected successes. Procurement has been impacted by the inflationary instability that has caused tenderers to weaken the quality of products they supply, to cover up on their eroded profits quoted before the implementation of the tender. In addition, in some instances, there were delays in the execution of the tender while payments could have been made. That could also be due to the inability to import some of the desired equipment from another country. Lack of capital for the purchase and maintenance of machinery also brought some challenges. As a result, buying second-hand or decommissioned equipment elsewhere has been the final choice, yet leading to many downtimes of the purchased machinery and shorter life spans. All those aspects have been hampering sustainable investment in the sector as was the case elsewhere (Rahman, 2020).

7.8. The need for balance toward sustainable development

The overall study was anchored by three theories, namely disaster risk reduction, corporate sustainability, and disaster risk reduction.

7.9. Disaster risk reduction and hydrogen

Disaster risk reduction assisted in addressing the necessity of investing in disaster risk mitigation to enhance resilience in energy systems amidst changing climate conditions. Hydrogen innovations can contribute to job creation and local development.

The global commitment to disaster risk reduction is articulated in the Sendai Framework for Disaster Risk Reduction (2015-2030) and its precursor frameworks to ensure sustainable development (United Nations, 2015). Priority 3 of the Sendai Framework primarily deals with the aspect of investing in disaster risk reduction towards attaining resilience. This framework underscores the critical nature of investing in disaster risk mitigation as a pillar of sustainable development (United Nations, 2015), compelling both public and private sectors to contribute to building a resilient society (Begum, Komoo and Pereira, 2012). To achieve that objective, both structural and non-structural measures are to be continuously implemented to enhance the economic, social, health, and cultural resilience of persons, communities, countries, and their assets, as well as the natural environment, particularly in Zimbabwe. The potential of hydrogen as a key innovation amid these efforts presents an opportunity for job creation, climate change risk mitigation, and localised development.

However, the reliance on imported technologies and equipment raises concerns about sustainability and self-sufficiency, often leading to a scenario where local resources are drained to support foreign supply chains. Within this context, the promotion of hydrogen technology should be ideally accompanied by efforts to enhance local production capabilities and empower communities to harness their renewable resources sustainably.

These measures form the drivers of innovation, growth, and job creation while they should further be more cost-effective and instrumental to save lives, prevent and reduce losses, and ensure effective recovery and rehabilitation. Hydrogen has the propensity to fulfill those expectations, and more innovation should be invested in the process to ensure sustainability, taking note that the disaster risk reduction concept feeds into the global sustainable development efforts. Innovation is key for sustainable development and more work should be done regarding hydrogen technology development as it has potential for mitigating climate change risk while the technology must still be continuously perfected. Sources of energy have always been equally a source of jobs to many people. Job creation remains at the heart of any resilient economy; as the economy grows, driven by innovation, it is important to promote green technologies as a risk reduction measure. In addition, Priority 3 (31) (c) notes that to achieve disaster risk reduction goals, it was important:

> "To promote cooperation between academic, scientific, and research entities and networks and the private sector to develop new products and services to help reduce disaster risks in particular, and those that would assist developing countries and their specific challenges …".

From the Pressure and Release model approach to disaster risk reduction, climate change poses a high risk of droughts, floods, and extreme temperatures among local communities in Zimbabwe (Mushore et al., 2021). That, therefore, requires localised strategies for risk reduction including disaster mitigation, prevention, and response. In that background, this study illustrates that hydrogen has potential for use both as an energy source and for strengthening disaster mitigation, prevention and response activities in a developing country context such as Zimbabwe and particularly in a rural setting.

The only fear is that equipment supplies will also form part of the long-term experiences summarised in the Dependence Theory (Romaniuk, 2017). That could be so, because whereas the electrolyser was developed as part of this study, its implementation and commercialisation required significant financial resources. In practice at the national level, investing in more electrolysers could mop up local financial resources due to the need to import the electrolyser components from the Global North. That has the propensity to derail national development efforts as was the main criticism leveled against the sustainable development templatic goals (Covert, Greenstone and Knittel, 2016).

Concerning disaster mitigation, prevention, and response, hydrogen is being used for data gathering for weather forecasting in Zimbabwe among other countries. The main challenge, however, is that the hydrogen electrolysers were supplied from the Global North in line with the general opaque configuration of the geopolitics of industrial production.

Africa is broadly endowed with mineral resources and solar PV generation capacity but largely lacks manufacturing and innovation capacity. As a result, the Global South largely remains the consumer in this respect, with challenges related to the unsustainability of the supply of equipment parts, while being dependent largely on technologies developed from the Global North. It is, therefore, true in line with the Sendai Framework that the technologies would assist developing countries, but the support is not yet more permanent but temporary. Previously, such support systems in Zimbabwe and South Africa have been impacted by global politics in cases where sanctions have been meted out on the given beneficiary countries (Qin, Di and He, 2022 and Zimbabwe Economic Policy Analysis and Research Unit (ZEPARU), n.d.).

In addition, Zimbabwe has an Agri-based economy that relies heavily on ammonium as a source of fertilisers, which are currently largely imported from other countries such as Russia and China to increase agricultural yields (Mushore et al., 2021). This is a strategy for disaster risk reduction, but the ammonium production must be localised, although the production further relies on electrolysers supplied from the North, while the hydrogen they were producing was basically not yet green.

Hydrogen can also reduce health risks among rural communities that predominantly use firewood for heating and cooking. Smoke from firewood poses threats of throat, lung, and mouth cancers, brain tumours in children, and the general depression of the human immune system (Maramura et al., 2020).

Zimbabwe has also been facing acute electrical power supply shortages for several years now (Maramura et al., 2020). That caused the disconnection of Sable Chemicals' hydrogen plant from the electrical power main grid. This eventuality further makes the issue of hydrogen production in Zimbabwe a long-term rather than a short-term issue. Where efforts for green hydrogen use have been put in place, they have been hindered by the electricity supply uncertainty, which caused the producers to revert to generators that were using fossil fuels.

In that respect, the achievement of the climate change mitigation objective is largely impacted negatively. Even where the electricity is available locally, a mix of hydro-power and thermal power forms the grid power that exists in Zimbabwe, and that means the grid power is neither green nor blue, which can further aggravate the devastating impacts of disasters. Green technologies can strengthen resilience against disasters and climate change (Begum, Komoo and Pereira, 2012).

7.10. Corporate Sustainability and Hydrogen

The theory of Corporate Sustainability exposed the challenges faced by corporate actors in balancing profit with the principles of sustainability, particularly in the hydrogen sector. This section evaluated how financial limitations impact the deployment and commercial viability of hydrogen initiatives.

Corporate actors in Zimbabwe’s hydrogen sector face challenges in balancing sustainability across the "triple bottom line" of people, planet, and profit. Profit has been achieved through government subsidies, and there is less emphasis on plant and product lifecycle management but profitability and synergies between broader national food security and sustained agricultural production including for export. Consequently, opportunities to utilise hydrogen in sectors like steel manufacturing remain underexploited.

Energy consumption levels, accessibility to grid power, and the prohibitive costs of hydrogen technology continue to impede corporate sustainability. Limited capital availability further complicates the deployment of hydrogen innovations, placing Zimbabwe's energy future at risk. Unless systemic barriers are addressed, such as poor infrastructure, high operational costs, and the dominance of fossil fuel interests, broad energy initiatives including hydrogen, will struggle to transition from rhetoric to reality in Zimbabwe.

Challenges that were being experienced revolved around the cost of accessing grid power, energy consumption levels involved in producing hydrogen, and the low production capacity of grid power in the country broadly. In the same respect, given the cost of hydrogen electrolyser production and operationalisation, corporate sustainability will remain low relative to hydrogen business projects in the developing world. That background is hinged among others, on the scarcity of low-cost financing for developing countries (Green Hydrogen Alliance, 2022). Further, limited supporting infrastructure, insecurity in the investment climate, lack of an enabling framework, the African regional concept for infrastructure and logistics, and dependence on crude oil, are among the many challenges facing Zimbabwe (Agbo, 2022). Those remain the significant hindrances to the successful implementation of hydrogen production projects in Zimbabwe and many other developing countries.

Funding models were still largely in the form of grants or private funding, although the uptake of such funds in the developing world was still low because of poor promotion of such innovation technologies locally and the nature of the funding, which was mainly driven from developed countries. Corporate sustainability in the hydrogen production industry in the Global South is thus still a long-term mirage, although markets exist.

The price of equipment and the production process costs are still too high for breaking even, and there continues to be the need to structure the business start-ups in a manner that the profits from hydrogen production and use can be realised indirectly, for example through the agricultural sector, while cooking and heating are not the primary concerns of the hydrogen production unless other support mechanisms exist towards justifying such a business case.

7.11. Sustainable Development and Hydrogen

The discourse in this study reflects on the urgent need for innovative solutions that align with the principles of sustainable development, underlining the significance of local innovation and equitable access to new technologies. Kraus (2020) asserts that development must consider not only current advancements but also future implications and challenges. In the context of hydrogen production in Zimbabwe, there is an urgent need for innovative solutions that resonate with sustainable development principles. As the discourse around hydrogen unfolds, it is paramount to ensure that interventions are grounded in evidence and contribute meaningfully to climate change mitigation. The expectation is that failures in past technologies should not dictate future opportunities. Instead, partnerships between the Global North and South must be fostered to facilitate local innovation and ensure equitable access to new technologies.

Without concerted efforts to adjust the balance of power in technology transfer and promote inclusive participation in sustainable development initiatives, hydrogen's potential as a transformative energy source may remain unrealised in rural Zimbabwe. Thus, focusing on innovation for sustainability is, therefore, key to new and future developments (Begum, Komoo, and Pereira, 2012). There is a high potential for hydrogen to revive the industry in Zimbabwe, and that can lead to job creation and climate change mitigation where the hydrogen will be greener as noted in the disaster risk reduction discussion section above (Agbo, 2022). The challenge is that most innovations were still being made largely in the Global North. There is also minimum cooperation with local academic, scientific, and research entities and networks and the private sector in the Global South despite the expectation for the opposite (United Nations, 2015).

Therefore, there is limited development of new products and services to reduce disaster risk in the Global South. These products that should assist developing countries in addressing their specific challenges are mainly from and for the North through the South economically.

That is however common in most sustainable development-associated frameworks as they are based on the principle of common but differentiated responsibilities (Garg, 2022). This allocation of responsibilities portrays the world as largely binary. The Global North therefore commits to funding Global South innovations although the question of the national interest continues to curtail whatever ambitions of the same global divide (Burchill, 2005). Thus, the possibility of adopting hydrogen for heating and cooking exists but sustainability of the concept is not yet guaranteed in the Global South. It is the researcher’s contention that intensified advocacy is warranted to narrow the gap between the Global South and the North. This can be achieved through enhanced and more inclusive strategic allegiances and collaboration in innovation, research, and development initiatives, against the perpetuation of the

Dependency Theory's ideas that keep the Global South at the periphery of development. This is a better answer to the clarion call for combating climate change-induced global warming through greening all development initiatives towards the net-zero carbon emissions target.

Therefore, the Global North should support the Global South to come up with the proof of concept, moving the ideas a step further to practice. In the meantime, brands being developed globally, are from the Global North. In addition, the initiative of creating hydrogen alliances with the South is still focused on supplying the product to the Global North and not for use in the Global South. Whereas that contributes largely towards the overall sustainable development goals, that may also equal mineral extraction taking place in many African countries, which forms feedstock for the Global North's development needs.

The only challenge is that the sources of green hydrogen energy are renewable through nature, which is directly important for human survival. These sources are water and air, and given that there are claims that some water bodies were already impacted by climate change, this provides food for thought regarding circumventing the challenge as the innovations are being developed.

Juxtaposing the disaster risk reduction thinking and the likely challenges presented by over-dependence on some renewable energy sources and, in particular, water and air in developing countries, there is also a need to ensure the road to sustainable development will not lead to risk creation. Ulrich Beck (1992) in his book *The Risk Society: Towards a New Modernity*, posits that the world is now living in a risky society in its quest for survival, which continues to attract further development. In that same mind, Kraus (2020) notes that catastrophe is anticipated to occur as a result of current forces that make the present better than the past.

Besides these arguments, the research acknowledges the fears but also argues that the world is naturally complex as articulated by the Complexity Theory (Bryne and Callaghan, 2014). Research should thus inform those fears that are largely informed by human senses without objectivity contrary to the reality that these innovations are also informed by research. Hence, research should remain the center of human development, while all caution for sustainability should be maintained to avoid unnecessary collisions in our tomorrow (Toffler, 1971).

7.12. Business Case for Hydrogen in Zimbabwe and Mukaratigwa Village

This business case outlines the potential for establishing a sustainable hydrogen production and utilisation framework in Zimbabwe, specifically focusing on Mukaratigwa Village. It aims to explore the economic viability and environmental benefits of transitioning to green hydrogen as a primary energy source while addressing the unique challenges faced in developing regions. The analysis includes cost considerations, funding sources, and strategic recommendations.

To justify a business case, it is also apparent that greening hydrogen production in developing countries can be taken as the next phase although the first phase should focus on developing technology efficiency, embraceability as an energy source among the other sources, as well as the development of its compatibility as current plants are still quite heavy, and requiring sophisticated transport that facilitates its loading and offloading from source to site.

Further, it should be noted that where corporates' source of funding is from the private market, they will continue to equally focus on market prices that allow them a break even. Therefore, climate funding should be channeled to start-ups to ensure innovations are also greened but with a business case in mind and towards profit, the planet, and the people. Otherwise in rural areas, the use of hydrogen for heating and cooking can be possible, but with a short-term contribution towards climate change as the assets have the risk of failure to run over a long period.

Respectively, it must be noted that some corporates which possessed electrolysers still have them. Nevertheless, they were no longer economical for hydrogen production for the local market due to deindustrialisation experienced in the country in the past decades. Deindustrialisation harms jobs locally, which translates to poorer households at the rural community level. That brings challenges to the business case for hydrogen for household heating and cooking in Mukaratigwa Village as a case study representative of many other rural communities in Africa.

7.13. Current Context

Zimbabwe's energy landscape is characterised by limited access to reliable and sustainable energy sources, particularly in rural areas. Mukaratigwa Village, like many other rural communities, relies heavily on traditional energy sources, which can be replaced or supplemented by green hydrogen. However, the local hydrogen production must address technology efficiency, affordability, and integration within the energy system.

7.14. Phase 1: Developing Hydrogen Efficiency and Compatibility

1. **Efficiency Improvement**:
    - Invest in research and development to enhance the efficiency of hydrogen production methods, such as electrolysis powered by renewable sources (solar, wind).
    - Collaborate with local universities and international experts to leverage technology transfer and innovation.

2. **Compatibility with Existing Infrastructure**:
   - Conduct an assessment of current energy systems to identify compatibility with hydrogen solutions.
   - Develop a modular approach to hydrogen systems that can be scaled up as demand increases.

7.15. Phase 2: Funding and Investment

1. **Funding Sources**:
   - **Climate Funding**: Target climate funding initiatives aimed at supporting green technologies. Allocate these funds to startups focused on green hydrogen production, ensuring the projects are profitable and supportive of environmental goals.
   - **Private Sector Investment**: Encourage private sector investment by demonstrating the potential return on investment (ROI) based on market demand for hydrogen as a clean energy source.
2. **Cost Analysis**:
   - **Initial Setup**: Estimate the costs associated with setting up selected electrolyser brands for hydrogen production, including technology acquisition, installation, and operational expenses. For example, the costs for electrolysers, renewable energy sources, and distribution infrastructure must be calculated.
   - **Break-even Analysis**: Determine break-even points based on market prices, potential subsidies, and the cost of traditional fuels. Include scenarios that consider fluctuations in the market.

7.16. Challenges and Solutions

1. **Deindustrialisation Impact**:
   - Address the historical deindustrialisation in Zimbabwe, which has potential impediments to scaling up hydrogen production. Engage with local communities to revive industrial activities that support hydrogen production and create jobs.
2. **Long-term Viability and Risk Management**:
   - Acknowledge the investment risks associated with hydrogen technology in rural areas. Develop a risk management framework to identify potential failures and implement contingency plans to sustain operations over time.

3. **Community Engagement**:
   - Promote community awareness and education on the benefits of hydrogen as a sustainable energy source for cooking and heating. Involve local stakeholders in the decision-making process to foster acceptance and support.

In ending the establishment of a hydrogen energy framework in Mukaratigwa Village, holds substantial potential for driving sustainable development and improving energy access. By focusing on enhancing production efficiency, securing funding, and addressing local economic challenges, this business case presents a viable route for integrating hydrogen into Zimbabwe's energy mix. Ensuring that the initiative is aligned with the principles of profit, planet, and people, will be essential for its success. The key steps involve detailed feasibility studies, community consultations, and initial funding applications if this vision is to be turned into a reality.

7.17. Sustainable development and energy in Zimbabwe

Despite its potential, hydrogen energy remains glaringly absent from Zimbabwe's National Renewable Energy Policy. This omission limits the effectiveness of sustainable energy initiatives, thus reinforcing perceptions that renewable energy development is relegated to sideshow status. The current policy framework seems focused more on rhetoric than action, undermining its intended objectives. Within this context, the call for anticipatory interventions becomes crucial. Proactive measures must be implemented to address ongoing energy challenges, rather than relying solely on reactive strategies (Tschakert and Dietrich, 2010). Transformative energy solutions must mend the social fabric of communities and address local needs.

Hughes (2023) argues, “If we want to fix a problem, we can’t afford to keep adding to it. If you’re in a hole, stop digging.” This assertion resonates with the assertion that more investment should be made in clean energy and that investment in fossil fuel energy should be curtailed. The aborted RE projects alluded to speak volumes of how much the energy sector is addicted to fossil fuels.

Policy in most instances appears to be premised on a post-apocalyptic vision. But anticipatory interventions are key in addressing the energy crisis. Responding to shocks might not be the best solution. Tschakert and Dietrich (2010) concur: “Learning by shock is neither an empowering nor an ethically defensible pathway.” Moreover, rural communities find themselves in a liminal space as energy challenges begin to be felt.

Writing about a post-disaster scenario, Gunning and Rizzi (2022) ask: “What does it mean to reconstruct a city after a natural, biological, or man-made disaster? Is the repair and reinstatement of buildings and infrastructure sufficient without mending social fabric?” The question is instructive when considering why rhetoric holds sway in the energy sector. It is critical that if RE is to make headway, the social fabric must be mended. Values and belief systems should be reconsidered.

7.18. H_2 Electrolyser, Rural Applicability, and Existing Energy Options

Hydrogen's central role in Zimbabwe's renewable energy discourse must be matched by actionable strategies for its generation and use among rural communities. This is also an international challenge. The electrolyser, designed for this study, demonstrates the viability of local hydrogen production particularly in Mukaratigwa village utilising the existing groundwater supply. Despite favourable conditions, reliance on indirect energy sources for electrolysis presents challenges, primarily concerning grid power reliability.

In that respect, water is predominantly available at no financial cost as no rates are paid to access the water. The underground water is portable and may require no further purification. Since water in these rural areas differs regarding salinity, alkaline water electrolysis technology is preferable because of its advantages of being less complex as a system when compared to the proton exchange membrane electrolyser. Despite these merits, the electrolyser also brings with it its demerits as discussed in detail in Chapter 2.

This aspect relates to the rural applicability of hydrogen production technologies. In the village that was adopted for this study, grid power exists. However, there were erratic supplies of power due to power cuts as part of the rationalisation of power use nationally. Solar and wind energy can also be tapped into for hydrogen energy generation. Other options available are off-grid diesel- or petrol-powered generators. The latter, however, is in this respect not preferred due to the carbon footprint that it will contribute to the environment. Beside the carbon footprint, continuous noise is also less preferable in the rural area. This is even more unfavourable in an urban set-up. As a result, grid power, solar power, and wind power are more appropriate for hydrogen production in rural Zimbabwe.

Wind power was mostly used in Zimbabwe pre-independence and immediately after independence. Insignificant investment has been made in that respect with time, except in a few farms in the country. As a result, investment in wind energy has remained relatively marginal. Vast tracts of land exist, and much of it is not being used productively. The eventuality is largely due to internal migration by the more active groups to towns and the reduced reliance on subsistence farming by most households in rural villages.

That as a result, further questions the causes of the reduction in investment in wind energy production systems in modern Zimbabwe. Other causes, borders around the way locals associate the different electrical energy sources with their level of success in society. Grid power is viewed to a larger extent as for the elite in the village, while solar due to its limitations with regards to consistency and lifespan of both the panels and inverters, was usually installed at the rural level. Solar power is often viewed as a subsidiary and temporary or a starting point, while the households await the grid-power installations.

Most of the rural people have, therefore, been relying on firewood and liquified petroleum gas among the energy mix that they might have been accessing, such as solar and grid power. Those who already have access to grid power were not fully utilising it except largely for charging cell phones and lighting. The rural people, therefore, have more needs that hydrogen alone may not fulfill until it is further developed to be more accessible and expanded in terms of its application in a typically modern household.

Heating and cooking are important aspects of hydrogen when fully developed for household use due to its chemical properties which makes it very dangerous unless the burners are also well developed for household safety. Most people in the rural areas were not even aware of hydrogen and more-so, its potential applications. Hydrogen is being learned in science subjects in high school education in Zimbabwe, but largely relative to ammonium production. That conscientisation of its applications is therefore important for its applicability in the future.

7.19. Hydrogen gas and the SDG No. 7 evaluation criteria

The United Nations acknowledges that sustainable energy access is an opportunity. That is true in the context of Zimbabwe, as is the case in many parts of Africa and Asia. Hydrogen energy in line with this study is therefore evaluated against the set UN Sustainable Development Goal number 7 criteria noted in Bamberger, Segone and Tateossian (2016) as follows:

7.19.1. Affordability

Hydrogen gas as a source of energy is in the meantime, given the parameters discussed in Chapter Four, not yet available and affordable in rural communities in Zimbabwe. The unavailability of hydrogen technology is synonymous with countries in the Global South. This can be attributed to a lack of capital and at times, the normal rhetoric by elites from both the Global North and the Global South, championing green energy solutions. Also, the unaffordability is due to the comparably high costs of the electrolyser, while the uses of hydrogen gas in the current context may only be limited to heating and cooking in domestic applications.

In addition to the electrolyser cost, this study establishes that the accessories still needed to be made more economically affordable by being available locally, for example, rather than through imports. Solar has not been installed for cooking but largely for heating and lighting, while hydrogen has the potential to close that gap if it becomes affordable. The technology, therefore, must be continuously perfected towards cost reduction.

For the technology to be operationalised it relies on importing most of its parts from the Global North while few parts are available locally and regionally (in South Africa). Yet the raw materials for manufacturing these components largely come from the Global South. Logistical support necessary is further costly hence the need for more support especially to the local communities whose use of the hydrogen gas is still far from being for true direct financial profit.

7.19.2. Reliability

Reliability of the hydrogen gas supplies in the village can be guaranteed by using solar energy, wind energy, and grid power as backups (Gul and Akyuz, 2020 and Chmielniak, 2019). Unfortunately, where grid power is used, the hydrogen would cease to be green since in Zimbabwe, the grid power is a mix of hydro-power and thermal power (Government of Zimbabwe, 2019). Given the electrolyser that was designed, the supply of hydrogen was supposed to be reliable, and mechanisms for ensuring constant efficiency levels of the electrolyser were still to be put in place.

It must be noted that as the equipment wears out, reliability may not be guaranteed which is why apart from the general operation of equipment, there is a need for constant manning and scheduled maintenance. Tragically, there has been a mushrooming of fake equipment in the country much to the chagrin of the consumers. That means an extra cost as someone should be dedicated to the place where the electrolyser will be situated to ensure that constant monitoring for efficiency is in place at any time of the day.

This study further provided a safety case (see Chapter 3) for the electrolyser, ensuring the reliability of the technology and the hydrogen gas at any point. This assists in avoiding potential risks that may jeopardise the functionality of the hydrogen generation and associated equipment.

7.19.3. Sustainability in the manufacture and everyday use of hydrogen

Hydrogen produced through the designed electrolyser was not meant for profit in the context of this study. That, therefore, presents the challenge of replacing any of the worn-out materials in the long term. Sustainability with regards to the lifecycle management of the equipment would need to be researched further and be made part of the suppliers’ delivery package upon equipment supply. The main challenge to that aspect is that some components of the electrolyser are procured from different suppliers.

In addition, the fact that the equipment is predominantly sourced abroad implies that, where politics surpasses business, hydrogen production work can be grounded. This has happened in some instances because of the sanctions imposed on the recipient country. As a business case supply sustainability can be more guaranteed where hydrogen is being supplied for a fee. In the Zimbabwean context, this is most important, and partly explains the resistance to get off the use of firewood among the local communities.

This technology will also reduce carbon footprint, but to ensure a balance between profit, people, and the planet, communities should be prepared to bear the cost of not polluting towards a sustainable future. That cost must be shared between the North and the South. Hence, there is a need to develop mechanisms to ensure the cost of sustainability is borne by both the rich and the poor to attain global energy justice.

Therefore, local partnerships for innovations with the innovators in the North, should assist in the sustainability of hydrogen production and use in Africa. Otherwise, there will be stranded assets in the longer term where hydrogen is embraced without consideration for its long-term use. The production of hydrogen requires more considerations for sustainability and this should be based on continuous research to establish the applicability of this concept on time, to anchor its rollout on scientific evidence. Early declaration of equipment weaknesses and a definable equipment lifespan from the suppliers should more-so strengthen the sustainability of hydrogen supplies and the functionality of the equipment.

7.19.4. Accessibility

Access to hydrogen energy requires developed and defined distribution pathways. That implies, the identification and establishment of the best means for energy distribution at the local level and the logistics related to supplies of any equipment that supports hydrogen production. It should be noted that the equipment is heavy and requires facilitative logistical planning and other arrangements to enable accessibility of the hydrogen production equipment and the hydrogen gas itself.

Accessibility is further enabled in this respect through the constant production and storage of hydrogen gas to ensure there is always a buffer. In this study, which was a pilot project, accessibility was facilitated through a funded scheme. The participants in this study were deliberately selected as a cluster and comprised of people in the village to leave no one behind. That further ensures that the study would not lead to the perception of bias over the choice of villagers eventually given access. Naturally, these villagers bear strong kinship ties.

The households accessing the hydrogen were, however, supposed to be prepared and oriented. Their households also had to be invested in appropriate facilities for the safe handling of the hydrogen gas in the home. Refueling is guaranteed by energy availability through uninterrupted power supply redundancy for continuous operation and seamless utilisation backed up by the centralised storage tank. This, however, adds to the cost of hydrogen gas. Skills transfer through training of local maintenance personnel to ensure they can repair and service the electrolyser adds to the strategies for guaranteed safe accessibility of the hydrogen gas at the community level.

7.20. Barriers, Opportunities, and Enablers for Hydrogen Innovations

Assessment of the barriers, opportunities, and enablers for hydrogen innovation revealed substantial gaps in sustainability and accessibility. Major technological developments continue to emerge primarily from the Global North, perpetuating reliance on imported products while limiting the benefits to communities in the Global South. There is an increase in hydrogen innovations that are leading to many patents that are being registered globally. Africa is, however, broadly excluded, and mainly OECD countries are involved in these technological developments. The hydrogen innovations and related technological developments prove that the Global North has remained at the center while the Global South is at the periphery. Brands discussed in Chapter Four confirm this pattern. To bridge these gaps, stakeholders must work collaboratively to address financial, infrastructural, and educational barriers that hinder technological advancements. Promoting local innovation, ensuring equitable access to resources, and facilitating knowledge transfer will propel Zimbabwe toward a sustainable hydrogen future.

7.21. Technological development

Whereas there are research institutions in Africa, and particularly in Zimbabwe, there has been limited upscaling of renewable technologies. Thereby, this has given credence to the argument of the renewable energy crusade as a Potemkin facade. Most of the technological innovations have remained well beneath the incubation stage and in many instances, limited financial resources are highlighted as among the barriers to the development of the technologies. Access to finances among renewable energy researchers and innovators remains a challenge. This raises many more questions, and could this be the aftereffects of what Freire noted as the negative bewitchment of the colonised through the Pedagogy of the Oppressed perpetuated in hegemonic tendencies of the ruling elite as tools of governance? (Herrmann, 2017 and Freire, 1970).

The pedagogy of the oppressed speaks to the type of knowledge that the masses can be given access to by those in the top echelons of power in society through the institutions of socialisation such as schools, colleges, and universities. Perpetuation of their ability to rule is normally at the core of the designed curriculum, yet weakens the long-term capacities of the society to decipher and stand for what is right over that which is wrong and largely colonial. In the context of global innovation and markets, the Global North is largely dominant as the manufacturer and supplier of industrial products as shown in Chapter 5. On the other hand, the Global South are mere users and consumers with less ownership of the means of production. Hence, reconfiguring the global political and economic capital markets to address the socioeconomic imbalances between the Global North and the South remains an important aspect of attaining global equality. That skewness of the global architecture against the Global South should be addressed as a matter of priority in national and international forums that seek to reduce global poverty.

The realisation of gaps leading to weak green technological development brings about the principle of common but differentiated responsibilities embedded in most international frameworks for sustainable development (Josephson, 2017). Moreover, the Global South should move from the old rhetoric of giving all faults to colonialism. It should instead address the challenge by implementing provisions of the international frameworks as a critical move for the realisation of overall sustainable development goals including sustainable energy development.

Cooperation between academic, scientific, and research entities and networks and the private sector in both divides of the globe, can assist in developing these products and services. Such cooperation should factor in the specific challenges in the developing countries in line with the Sustainable Development Goals. A stagnated industry nevertheless further impacts the innovation capacity of the academic, scientific, and research entities, demotivating new knowledge generation and development.

Institutions for research, innovation, and technology development largely exist in Africa and Asia, and some of these institutions were initially developed with support from the Global North. Further, these institutions have a large potential supply of manpower. However, the Global South must move away from the mass production of education and the training of graduates largely for the services sector. There should be a shift towards education for production and value addition, towards a more sustainable socio-economic and human development (Freire, 1970).

Key enablers therefore are increased funding, reconfiguration of pedagogies, and support for partnerships which are already there yet requiring shifts in the quality of knowledge content and knowledge transfer mechanisms. Partnerships are important given that consciousness of new technologies and technological developments beyond those popularised in media, is weak. This is prevalent even among most of the expected practitioners, who have tended to be more technological users or consumers than innovators.

7.22. Technological deployment and commercialisation

The Global South is included in the hydrogen technology deployment and commercialisation agenda. Market penetration was broadly achievable through donations from the Global North at initial stages, and then market uptake with time. In essence, the cost of hydrogen generators was still high, making them less accessible in the Global South. The Global South continued to lag at the technological development stage and, therefore, would be the consumer rather than the prosumer of the technology.

Respectively, benefits derived by the Global South from the sustainable development agenda may keep it at the periphery as it is unable to restructure the global architecture but to maintain the status quo. As a result, less will be derived from the innovations but only as will be derived by the technological distributors and the final users of the same technology. Distributors of the technologies (both hardware and software) are still more from the Global North which means the North still has the bigger share of the distributors of these technologies.

Some innovators have been renting their technologies, while others have been selling their equipment and releasing their ownership rights once purchased. Adaptation required for sustainability is also difficult where technology ownership rights remain fully owned by the supplier. That reduces the opportunity for exploring such technologies where other partnership avenues are also unavailable.

Therefore, the tale of stranded assets will continue to be experienced in the Global South as the inconsistent dependence from the North will continue to be perpetuated, including through the Sustainable Development Agenda. As a result, the Global South is sometimes hellbent on putting on a sideshow that helps the elites achieve political expediency and acceptability in the League of Nations through sustainable development diplomacy.

Those aspects add to the barriers to green hydrogen technology development. Mistrust, resulting from past experiences, can also create hesitancy in adopting such noble technologies as long as the Global South is viewed only as the consumer. Hence, the tragedy of what novelist Chimamanda Adichie terms "The Danger of a Single Story."

Previously, the superiority of global politics has overridden business agreements. That has further remained a barrier to adopting technologies deployed and commercialised in the South. Noting that, in reality, more local distributors have to be strategically stationed. Otherwise, with time, the market will be flooded with counterfeit equipment. Further reducing interest in the new technology as efficiency levels can be reduced as noted earlier in this chapter.

7.23. Chapter Summary

The sustainable energy development policy in Zimbabwe, as is the case in most African countries, requires a paradigm shift from performative gestures to substantive actions that improve local energy access and promote technological independence. The hydrogen sector, positioned within the broader discourse of sustainable development must be supported by inclusive policies and community participation. This study underscores the urgent need for governments' fundamental shift in approach to sustainable renewable energy development, particularly regarding hydrogen. The existing policy framework must transition from rhetoric to action, prioritising impactful interventions that address the nuanced realities of rural communities. By examining the interplay of local experiences, global dynamics, and innovative potential, this research asserts that hydrogen can be a pivotal element in the sustainable energy landscape if coupled with a commitment to genuine social and economic transformation. The study further highlights that despite the challenges and ongoing barriers, there is viable potential for hydrogen to play a transformative role in the renewable energy transition. Enhanced engagement with local actors, rigorous policy development, and a commitment to equity and sustainability are essential for ensuring that Africa not only meets its energy needs but also contributes meaningfully to the global climate agenda. By critically assessing the nuances of Zimbabwe and Africa's broad energy landscape and the obstacles to sustainable development, this chapter argues for a comprehensive approach that recognizes the complexities of both local and global contexts, ultimately paving the way for a more resilient and sustainable energy future anchored in hydrogen. The chapter framed these discussions within a broader context of socio-economic challenges and environmental sustainability, serving as a pathway for future research and actionable policy development in Zimbabwe and other similar developing country scenarios.

CHAPTER EIGHT

8.1. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS: ANOTHER ENERGY IS POSSIBLE

This is the overall concluding chapter for this thesis. It synthesises the insights gained throughout this thesis, reflecting on the potential for transformative energy solutions within Africa and particularly Zimbabwe's current energy landscape, broadly taking a cue from the discussion in Chapter Seven. The analysis presented in previous chapters illuminated the pressing energy crisis facing developing nations, characterised primarily by an overreliance on hydro and thermal power sources, which present unique sustainability challenges. Drawing from Sweeney's (2018) assertion that "another energy is possible," the study concludes that hydrogen has potential as a viable alternative that could complement existing renewable energy sources like solar and wind. By examining the technological, economic, and social dimensions of hydrogen utilisation, this research laid the groundwork for the practical implementation of a local green hydrogen production and use system, particularly in rural settings such as Mukaratigwa Village. The thesis argues that while the potential for hydrogen is significant, its successful adoption hinges on creating the right conditions for safe usage and community acceptance. This chapter encapsulates the study's key findings, and their implications for the sustainable development goals, further outlining the necessary steps for establishing a robust green hydrogen economy in Zimbabwe. The presented reflections (conclusions) and recommendations serve as a clarion call to action for stakeholders across sectors. Stakeholders are recommended to participatorily collaborate in developing policies and frameworks that facilitate the global agenda to transition towards cleaner and more sustainable energy sources.

8.2. Introduction

This study concludes that another energy is possible especially given that Africa, and more specifically Zimbabwe, experiences a crippling energy crisis. The phrase "another energy is possible," borrowed from Sweeney (2018), encapsulates the study's core argument that hydrogen could emerge as a significant element in Africa’s energy matrix. Currently, Zimbabwe primarily depends on hydro and thermal power, with the latter significantly contributing to greenhouse gas (GHG) emissions. In this context, transitioning to green energy, specifically hydrogen, is imperative. Thus, with the sustainable development goals very much in vogue, this study argues that another energy (hydrogen) is possible. The thesis’ thrust emphasises that while hydrogen holds substantial potential as a complementary energy source alongside existing renewable options (such as solar power and wind power), its successful adoption hinges on addressing noted challenges and promoting the exploitation of available opportunities. Therefore, more must be done to resolve the root causes of energy challenges, while fostering cooperation frameworks is crucial to achieving Sustainable Development Goal No.7 which must guide future energy policy and practice.

8.3. Summary of chapters

This thesis comprises eight chapters that collectively respond to the core research question presented in Chapter One. The following summaries provide an overview of the main findings from each chapter:

8.3.1. Chapter One

Chapter One gave the introductory synopsis of the thesis by outlining the background of this study, emphasising possibilities for utilising hydrogen as an energy innovation to address renewable energy scarcity in Africa. It established essential links between energy access, sustainable development, disaster risk reduction, and corporate sustainability. The main findings drawn from this chapter are:

- the renewable energy scarcity in Africa, and particularly in the case of Zimbabwe is a reality;
- grid power generation capacities are largely low compared to market needs and that causes more reliance on fossil fuels which contribute to high greenhouse gas emissions;
- there is a strong nexus between energy access, sustainable development, disaster risk reduction and corporate sustainability;
- the energy insecurity puzzle must be broken if the developing world's innovations should achieve overall sustainable development, and;
- the Global South's energy innovation initiatives are largely negatively affected by the challenge of balancing between Egalitarianism and Libertarianism as approaches to development and poverty alleviation.

8.3.2. Chapter Two

Chapter Two discussed the theoretical landscape of hydrogen technology development. It highlights how energy drives development, addressing historical and current trends in hydrogen production and supply chain. The study acknowledges the inherent hydrogen potential and reveals the positive trend in the growth of hydrogen use at both industrial and household levels. Negative aspects of hydrogen embraceability are being dealt with through various ongoing research. Key findings from Chapter Two include the fact that:

- main fossil fuels used throughout history including in the Global South are wood, coal, oil, and natural gas;
- there is emphasis on the need to replace fossil fuels with renewable energy sources such as hydropower, wind energy, geothermal power, solar, non-woody biomass such as biogas, tidal energy, and hydrogen energy among others;
- there is a dearth of literature on other sources of renewable energy such as nitrogen, helium, and nuclear, in many parts of Africa;
- the most common hydrogen generation methods are steam reforming, partial oxidation, auto thermal reforming, water gas shift, preferential oxidation, and methanation;
- pyrolysis, co-pyrolysis, and electrolysis are among the main technologies for hydrogen production;
- electrolysis has been in use for over 200 years;

- the four main types of electrolysers (popularised) are Alkaline Electrolysers, Proton Exchange Membrane, Anion Exchange Membrane, and the Solid Oxide Electrolyser although Alkaline Electrolysers and Proton Exchange Membrane electrolysers are already more developed and available on the market, and;
- Alkaline Electrolysers are more straightforward to operate and maintain but they are less effective when compared to PEM.

8.3.3. Chapter Three

Chapter Three delves into the methodological framework, detailing the mixed-methods approach adopted to gather both qualitative and quantitative data. The significantly designed alkaline electrolyser that served as a prototype for hydrogen generation in this study, is also presented in this chapter. The thesis is a result of both engineering and social science as a prototype electrolyser was designed, and the parameters used to deduce the potential for using hydrogen gas in rural Zimbabwe were outlined. Key findings for this Chapter are that:

- existing Alkaline Electrolysers on the market are still costly and bulky in terms of mass and volume, which discourages their movement to many parts of Africa;
- in practice, during deployment of the electrolyser, experts are supposed to support the installation, commissioning process, and running of the plant, which makes the Electrolyser deployment for individual research more difficult in the Global South;
- the designed electrolyser and implemented baseline study laid the foundation for any successful experimental study and deployment of an electrolyser in rural settings as that would provide an understanding of the unique context of the heterogenous target areas in Africa, and;
- conducting a hydrogen production experiment requires investment in other support systems for its production, storage, distribution, and use, as well as defined safety standards and procedures since hydrogen gas is highly flammable.

8.3.4. Chapter Four

Chapter Four provides a global assessment of the hydrogen market, focusing on technological developments revealing the predominance of Alkaline and Proton Exchange Membrane electrolysers. Chapter Four surfaces the following findings:

- there are challenges associated with reliance on foreign manufacturing for these technologies, particularly daunting the Global South countries' efforts around greening them;
- many hydrogen electrolyser brands and associated models exist even though they largely depend on other manufacturers for electrolyser component feedstock, making it difficult to control the energy supply chain for total greening;

- dominant electrolyser suppliers hail from the Global North and they are members and affiliates of the OECD, which generally makes the Global South mere users who are neither manufacturers nor suppliers of resultant technologies;
- in Africa, South of the Sahara, only around five countries that were affiliated with the OECD were the ones more involved in hydrogen innovations;
- the raw materials used for manufacturing RE supply chain equipment are generally extracted through mining in the Global South;
- there is a need to deliberately increase the involvement of the Global South in the hydrogen innovation process to ensure no one is left behind in seeking solutions toward achieving sustainable development goals;
- innovators were generally creating mechanisms for enabling the embraceability and distribution of their technologies while big companies were largely buying some of the technologies from innovators for further development and commercialisation, and;
- there is a general rise of participants in the hydrogen supply chain, with more patents suitable for scaling up being registered in many countries, such as China, depending on their industrial policies.

8.3.5. Chapter Five

Chapter Five assesses the current state of hydrogen production and usage in Zimbabwe, revealing that local hydrogen production has become limited and largely dependent on imports from South Africa. The chapter illustrates the implications of the energy sector's structural weaknesses on hydrogen initiatives. Key findings are summarised below:

- Zimbabwe previously produced hydrogen for ammonia that was used as feedstock for ammonium nitrate fertiliser manufacturing with downstream effects on the local industry;
- the Zimbabwean industry used hydrogen for hydrogenation and gas chromatography in margarine and detergent-making processes, power plant applications for turbine armature windings cooling, and in the meteorological services industry to power hydrogen weather balloons;
- government subsidies were sustaining the companies that were producing hydrogen, and these subsidies were scrapped with time, citing the opportunity cost of electrical energy consumption in other industries;
- the increased number of household users of electrical energy post-national Independence and failure to continue to expand the electricity supply capacity for the country contributed to the policy position of scraping government subsidies;
- Zimbabwe’s main sources of energy for cooking and heating are biomass, coal, petroleum products, and electricity from hydro, thermal, and solar;

- only around 19% of the electrical power was being accessed in rural areas due to the cost of expanding the accessibility of the national electricity grid coupled with an energy supply deficit emanating from inadequate installed generating capacity;
- pursuits for hydrogen production in Zimbabwe were being impacted negatively by the cost of producing electricity, which had ripple effects on the tariff of electricity accessed by consumers;
- infrastructure for hydrogen production, storage, and transportation is still in existence but has been relegated to white elephants of late, with some of the idle hydrogen production plants already decommissioned;
- in some cases, parts of decommissioned electrolysers were being exported and reused to establish similar plants in other international jurisdictions, and;
- with the developing industry, there was potential for a hydrogen market in the country since the previous adverse effect on hydrogen investment emanated from deindustrialisation in Zimbabwe.

8.3.6. Chapter Six

Chapter Six shifts the focus to Mukaratigwa Village, exploring local perceptions of hydrogen and energy-sourcing patterns. It highlighted the village's heavy reliance on firewood and presented evidence of community interest in hydrogen solutions. Below are the main findings from Chapter Six:

- there is less knowledge on hydrogen as an element and its uses among the rural population in the village, and those knowledgeable firmly held that it was not safe for household application;
- most households used firewood for cooking and heating due to the household's economic position that underpins the prevailing energy use patterns, although the household required energy for different purposes;
- in the village, fetching the fuel for heating and cooking was not restricted to the girl child or the mother alone, but even the fathers were responsible for that task;
- the inequalities between the haves and the have-nots manifested in the differences in the firewood fetching cultures and specifically the frequency of fetching the energy source at the household level;
- besides energy for cooking and heating, charging cell phones, powering television sets and radios, charging lights used for children's studies, general household lighting, and refrigeration were among the common uses of energy in the village;
- hydrogen functions suit the energy demands of rural communities even though the high cost of the hydrogen supply chain remained a challenge for deploying the technology to rural areas that lacked economic means for general self-sustenance, and;
- there were high levels of appreciation and willingness to use the technology among the rural communities as established through the baseline survey.

8.3.7. Chapter Seven

Chapter Seven provides a synthesis of findings from the preceding chapters that formed this thesis. It critically examined and assessed the renewable energy policy landscape in Zimbabwe and the viability of hydrogen in that context. This chapter shows that the Renewable Energy Policy in Zimbabwe was silent on the country's position and steps for hydrogen technology development. In addition, it discusses the theoretical framework adopted for the study in line with the general aspects generated throughout the other chapters. This study further broadly assessed Zimbabwe's position concerning the Sustainable Development Goal Numbers 7 (Affordable and Clean Energy), 9 (Industry, Innovation and Infrastructure), 13 (Climate Action), 15 (life on land), and 5 (Gender Equality). The Chapter further offers a discussion of the overall study. Key highlights include:

- localised strategies for risk reduction, such as the development and implementation of hydrogen technology, are better inclusive of locals to ensure ownership for sustainability;
- as long as the nexus between disaster risk reduction, sustainable development, and corporate sustainability is not adequately knitted, neither of the three will achieve sustained long-term benefits;
- the conditions for hydrogen production in Zimbabwe are conducive, especially given that grid power, solar, wind energy, and water as an electrolyte are available;
- wind energy is available in the country, but there was less uptake among the rural population and mainly for household use except in farms and for very few community project water pumps;
- hydrogen meets the criteria for SDG 7, which are affordability, reliability, sustainability, and accessibility as long as continuous and conscious investment in the energy sector is made at local, regional, and intercontinental levels;
- there is a gap in collaboration for technology development and knowledge transfer between the Global North and the Global South, and;
- collaboration is critical for avoiding risks previously faced where national and global politics override collective rationality which underpins sustainable development.

8.4. Conclusions

The study affirms that hydrogen occupies a central role in the renewable energy discourse, particularly for its potential to tackle the 24-hour energy needs of communities. Unlike solar and wind energy, which depend on specific conditions, hydrogen can be a reliable and/or complementary energy alternative. Solar energy is mainly generated when there is sunshine. By and large, Zimbabwe is a landlocked country, and some parts of it have limited potential for generating wind energy. The study suggested that the eastern highlands experience better wind speeds and possess greater wind energy harvesting capacity for Zimbabwe. However, not much has been done to simulate and harness wind energy in the country.

This thesis interrogated whether sustainable renewable energy development in Zimbabwe is a sideshow or a Potemkin facade. Despite the policy frameworks addressing renewable energy, progress in implementing some green technologies has been limited. The dominant use of firewood for cooking and heating has led to alarming deforestation trends, indicating a pressing need for alternative energy solutions.

An ethnographic mixed-method approach underpinned this study, which sought deeper insights into the feasibility of hydrogen adoption in rural areas. The study aimed at trying to understand things differently. Insights gained reflect a commitment to understanding what constitutes success in the renewable energy discourse, a success that promises to mitigate climate change and reduce poverty. It offers insights into what counts in the renewable energy discourse, rather than seeking to count, to borrow a phrase from the African academic Francis Nyamnjoh. Ultimately what counts in the renewable energy discourse constitutes success.

Success is critical in a changing climatic environment. Success means less rhetoric and more action. This study invokes Gonzalez (2012). Grappling with what constitutes successful climate change adaptation, Gonzalez opines “The science of adaptation; there is no revenge like success”. This study rephrases the above quotation this way: “The science of renewable energy; there is no revenge like success”. Undoubtedly, the successes in energy generation through renewable sources such as hydrogen can play an essential role in reducing poverty. Today, all forms of energy generation are sprouting together. These include gas, oil, coal, nuclear, and renewables. The global demand and need for green energy continue to grow.

The overarching argument of this study reaffirms that "another energy is possible," particularly in the context of a rapidly changing energy landscape exacerbated by climate change. ‘Another energy is possible’ has been the rallying cry of this thesis as rural communities find themselves having to adapt to a disruptive new reality. Hydrogen represents a viable solution that can complement existing renewable energy sources. However, realising the potential of hydrogen requires immediate action to mitigate the ongoing energy crisis while simultaneously addressing inequities within Zimbabwe's energy landscape.

As Zimbabwe moves forward in its energy transition, the sustainable development agenda must not remain a mere rhetorical exercise. It should yield real, equitable benefits for all stakeholders involved, especially through North-South collaboration. Scaling-up of renewable energy interventions is moreover constrained by several factors, some of which are institutional. Failure to incorporate and execute renewable energy solutions, which are part of most national strategic master plans, could have dire impacts on rural livelihoods and the global climate change mitigation and adaptation drive. In ending, the current energy crisis in Zimbabwe shines a glaring light on the entrenched fragilities and inequalities of communities. The need to come up with new sources of energy beckons and whether to embrace it or not is the question. This study only laid a foundation that would need further development, optimisation, and operationalisation.

8.5. Recommendations

The recommendations provided in this thesis pave the way for stakeholders to collaboratively create a sustainable energy future, enabling communities, particularly in rural areas, to thrive in the face of contemporary challenges. Based on the study findings, the following recommendations are proposed:

1. ***Enhance Collaboration:*** Strengthen cooperation between research institutions in the Global North and South to facilitate knowledge transfer and innovation in green hydrogen technology.
2. ***Develop Supportive Funding Models:*** To encourage the transition from fossil fuels, create friendly funding models for green energy initiatives in the Global South.
3. ***Pilot Hydrogen Projects:*** Implement pilot hydrogen projects in Mukaratigwa Village to gain insights into practical applications and community acceptance.
4. ***Invest in Hydrogen Research:*** Allocate resources for research focused on optimising hydrogen production technologies for rural contexts.
5. ***Promote Awareness and Training:*** Educate communities about hydrogen's potential as an energy source, and foster a culture of safety and acceptance.
6. ***Strengthen Policy Frameworks:*** Revise national energy policies to explicitly include hydrogen as a renewable component, ensuring a cohesive approach to sustainable development.

8.6. Dissertation's Contribution to Knowledge

The thesis contributed to knowledge in several ways. These contributions resonate around academics, policy, and the domain of practice.

- **Academic Contribution:** The interdisciplinary nature of the study bridges engineering and social sciences, offering practical insights into hydrogen deployment in rural contexts. Consequently, the study provided a scenario whereby feedback is accessed from the user's perspective. It lays the groundwork for further research on hydrogen's potential role in energy innovation, contributing to the discourse on sustainability from a perspective that a solution has been developed and must be implemented. This discourse becomes practical and straddles the engineering and social sciences disciplines. Such knowledge generation is necessary for sustainable development and seeks to test the applicability of the designed hydrogen electrolyser in a rural setting. In addition, the study led to the design of an alkaline electrolyser and advanced aspects that should be improved on most of the electrolysers on the market cognisant of conditions prevailing in the Global South. The improvements include mechanisms for easy handling since the electrolyser is heavy. The acrylic end plates in the design were reinforced deliberately and skilfully with perforated steel plates. The designed electrolyser awaits deployment for optimisation and overall hydrogen production and uses via experimentation.

- **Policy Contribution:** The study highlights significant gaps within Zimbabwe's (realities experienced in Africa) renewable energy policy framework, specifically the neglect of hydrogen technology. These realities impact the implementation efforts of the overall Sustainable Development Goals. It underscores the importance of an actionable policy that embraces hydrogen as part of the national energy strategy. The analysis reveals a lack of government action in investing in hydrogen technology in response to the global enthusiasm for green energy solutions. It highlights a significant exclusion of the Global South from current clean energy initiatives, which may foster resentment towards new technologies in the future. The exclusion undermines global climate change mitigation and adaptation efforts, hindering collective action and slowing the progress needed to meet international carbon neutrality goals. The study emphasises the importance of monitoring the hydrogen energy debate, technological developments, market integration, and the enhancement of government policy frameworks. It identifies policy gaps at national and international levels that, if unaddressed, could impede the advancement of hydrogen technologies globally.

- **Community of Practice Contribution:** This research serves as a foundational case study for practitioners in climate change and energy sectors, and provides actionable insights on how hydrogen innovations can be integrated into local energy systems. Aspects around what works better and what does not work in the short, medium, and long term were also discussed. That should assist in forecasting the future of hydrogen and the energy development question as solutions are being sought to deal with the global energy challenge towards sustainable development. In developing energy interventions for sustainability, this study was also useful for practitioners such as climate change interventionists, sustainable development advocates, and engineers involved in technology innovation, scaling up, and commercialisation. Thus, setting the stage for conversations towards establishing models that promote cross-pollination of ideas and cooperation in research, innovation, and development of green energy technologies, their deployment, and use. The study also exposed unethical and predatory conduct due to the proliferation of unsanctioned middlemen, dumping counterfeit products purporting to be from original equipment manufacturers (OEMs). That was being facilitated by OEMs whose products were, to a larger extent, concentrated only in developed countries with limited distributorship in the developing world. Ultimately, this form of exclusion creates resentment toward new technologies by the majority of potential Global South users in the long term. Users' bad experience with inappropriate equipment breeds mistrust and negates confidence building and embraceability of cleaner energy innovations.

8.7. Implications for further studies

The inability to innovate solutions to bridge identified gaps will likely result in developing nations falling behind in renewable energy policy advancements. Consequently, critical targets may be missed, opportunities for growth at various levels diminish, and long-term policy failures ensue; hence, there is a need for further study in this area that focuses on eradicating the ideas of dependency theory.

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APPENDICES

APPENDIX A

QUESTIONNAIRE

The researcher, Edmond Mkaratigwa is carrying out a PhD study entitled **Possibilities for Using Hydrogen as an Energy Innovation and Accessibility Solution for Sustainable Development in Africa**. He is studying with SWANSEA University. All information supplied in this Questionnaire will be treated confidentially and solely for purposes of this research. You are kindly requested to answer the following questions as honestly as possible, by ticking the appropriate box.

1. State your age group
   - ☐ 7 to 16
   - ☐ 17 – 35
   - ☐ 36 – 65
   - ☐ Above 66

2. What is your marital status
   - ☐ Married
   - ☐ Single
   - ☐ Divorced
   - ☐ Widowed

3. What source of energy do you mainly use in the home for heating and cooking?
   - ☐ Fire wood
   - ☐ Gas
   - ☐ Grid Power (Electricity)
   - ☐ Solar power

4. What is your Second main source of energy for heating and cooking?
   - ☐ Fire wood
   - ☐ Gas
   - ☐ Grid Power (Electricity)
   - ☐ Solar power

5. If your answer in either question 4 or 5 is Gas then specify the type of gas
   - ☐ LPG
   - ☐ Bio gas
   - ☐ Hydrogen
   - ☐ Any other

6. State any other uses for which you need energy (electric power) in the home.
   - ☐ Cell phone charging
   - ☐ Radio/TV & Video games
   - ☐ Ironing
   - ☐ Lighting
   - ☐ Sewing machines

7. How do you access your main source of energy for heating and cooking?
   - ☐ Buying
   - ☐ For free
   - ☐ Both Buying & Free

8. Who mostly gets your household source of energy? (eg father)……………………

9. How often do you source your main household energy source for heating and cooking per month? (eg 10 times a month) ………………………………………………………

10. How much time in hours do you take in sourcing your main source of energy for cooking and heating whenever you do so? …………………………………………………….

11. How often do you source your second source of energy for heating and cooking per month? (eg 10 times a month) …………………………………………………………………….

12. How many people are always present for a standard meal as part of your household?
    - ☐ 1
    - ☐ 2
    - ☐ 3 to 5
    - ☐ Above 5

13. How many meals do you prepare on a normal day?
    - ☐ 1
    - ☐ 2
    - ☐ 3
    - ☐ 4

14. On average how much time do you need to prepare One standard meal for the household?
    - ☐ Less than 1Hr
    - ☐ 1Hr
    - ☐ 2Hrs
    - ☐ 3Hrs
    - ☐ Above 3Hrs

15. Given the availability of the sources of energy listed in number 5 above, which one do you prefer most?
    - ☐ Fire wood
    - ☐ Gas
    - ☐ Grid Power (Electricity)
    - ☐ Solar power

16. Have you ever heard that hydrogen can be used as a source of energy for heating and cooking?
    - ☐ Yes
    - ☐ No

17. If you answered yes on question 16 above, how did you first hear about hydrogen as a source of energy for cooking and heating?
    - ☐ Social media
    - ☐ Broad cast / print Media
    - ☐ Community Members
    - ☐ School
    - ☐ Family members

Thank You

End of Questionnaire

APPENDIX B

Interview Guide

1. What are the main/major sources of energy for households in this area or in your locality?

2. Why do most people adopt use of the current main sources of energy in this area nowadays?

3. Let us say you have access to hydrogen, describe your positive and negative imaginations of the first day you will use it as a source of energy in your household?

4. What are the main challenges you face as a result of each source of energy currently being used by most households in this area?

5. Describe what you understand as development in this area regarding sources of household energy?

6. What are your other comments regarding use of Hydrogen as a source of energy in this area?

End of Interview Guide

APPENDIX C
Identified Electrolyser brands on the Global Market

Company	Country	Type	Model	Capacity [Nm^3/h]	Capacity (Kgs/h)	H_2 Output Pressure [bar/g]	H_2 Purity [%]	Electrical Consumption [kWh/kg H_2]	Electrical power rating (KW)	HHV Efficiency [%]	Water Usage (Kgs/h)	Cost (£)
Acta	Italy	AEM	EL1000	1	0.088	29	99.94	53.2	5	74%	1	34000
Angstrom Advanced	USA	PEM	HGH170000	10	0.88	4	99-99.9999	64.5	50	61.4%	10	150000
Elogen (ex AREVA H2 Gen)	France	PEM	ELYTE 10	10	0.88	30	99.999	47.8–60.0	50	65.6–82.4%	10	165000
Enapter (ex-Acta)	Italy	AEM	EL2.1	210	18.48	35	99.8	48	1050	73.9%	210	340000
Erredue	Italy	PEM	SIRIO 200	2	0.176	15 (Opt. 30)	99.99	53.3	10	73.9%	2	72000
GreenHydrogen	Denmark	PEM	Hyprovide P1	1	0.088	50	>99.995	61.2	5	63.0%	1	35000
H-TEC SYSTEMS	Germany	PEM	EL30/144	3.6	0.3168	29	N/A	55.4	18	71.1%	3.6	98000

Idroenergy	Italy	Alkaline Water Electrolysis	mod. 8.0	5.33	0.46904	4	>99.5	62.5	26.5	63.0%	5.33	124000
ITM Power	UK	PEM	HGAS3SP	3.2	0.2816	N/A	99.999	N/A	16	N/A	3.2	87000
Nel Hydrogen	Norway	PEM	H6	6	0.528	15 (Opt. 30)	99.9995	75.5	30	52.2%	6	
Pure Energy Centre	UK	Alkaline Water Electrolysis	$4Nm^3$	4	0.352	Up to 12	>99.3	62	20	63%	4	120000
Sagim	France	Alkaline Water Electrolysis	M5000	5	0.44	7	99.9	55.6	25	70.8%	5	124000
Teledyne Energy Systems	USA	Alkaline Water Electrolysis	NH-450	450	39.6	10	N/A	65.6	2250	60.2%	450	980000

Wasserelektolyse	Germany	Alkaline Water Electrolysis	EV150	225	19.8	1		~5.3	1125	~55%	225	760000
Hydrogenics	Canada/EU	Alkaline Water Electrolysis	Hystat60	60	5.28	Oct 25		~5.2	300	~60%	60	250000
Mc Phy	France	Alkaline Water Electrolysis	-	60	5.28	10		~5.2	300	~60%	60	249000
Teledyne Energy	USA	Alkaline Water Electrolysis	SLM1000	56	4.928	10		N/A	280	N/A	56	300000
Siemens	Germany	PEM	E60	60	5.28	30		~4.9	300	~60%	60	340000
Areva H2Gen	France	PEM	E60	60	5.28	30		~4.9	300	~60%	60	344000

Proton Energy Systems	USA	PEM	Hogen C30	30	2.64	30		~5.8	150	~50%	30	320000

Source: Adapted from Pietra *et al*. (2021) and Godula-Jopek (2015) and Author (2023).

APPENDIX D

Correlations

Correlations

		lnEfficiency	lnOutput
lnEfficiency	Pearson Correlation	1	-.574*
	Sig. (2-tailed)		.040
	N	13	13
lnOutput	Pearson Correlation	-.574*	1
	Sig. (2-tailed)	.040	
	N	13	13

*. Correlation is significant at the 0.05 level (2-tailed).

```
CORRELATIONS
  /VARIABLES=lnEfficiency lnOutput
  /PRINT=TWOTAIL NOSIG FULL
  /CI CILEVEL(95)
  /MISSING=PAIRWISE.
```

Confidence Intervals

	Pearson Correlation	Sig. (2-tailed)	95% Confidence Intervals (2-tailed)[a]	
			Lower	Upper
lnEfficiency - lnOutput	-.574	.040	-.855	-.033

a. Estimation is based on Fisher's r-to-z transformation.

APPENDIX E

E ESRI-RICE-H_2NRG deployable electrolysis system assembly instructions

E1 Introduction

The pilot scale, containerised, H_2/O_2 electrolysis system is almost entirely custom built at Swansea – there are some significant items that are 'off the shelf' but the core items are built 'in house' consequently here in is a guide that details all parts of the units' construction and its assembly.

E2 Electrolysis stack

The stack is comprised of the following component parts:

1. Insulator plates

Laser cut from 5mm acrylic, 600mm x 620mm, to prevent stainless steel bolts from shorting the stack. These are placed at each end of the stack. There are cut outs in the insulator for conductor connections, pipe fittings and lifting straps

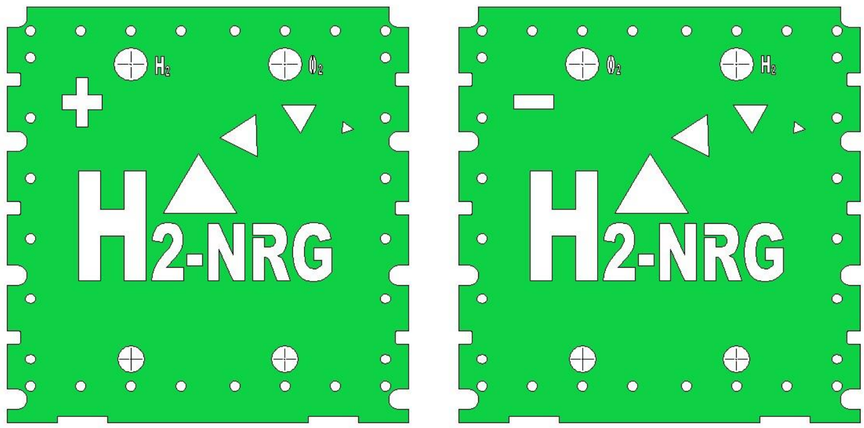


Figure 2. Insulation plates

2. Endplates

Laser cut from 10mm stainless steel plate, 600mm x 620mm, to provide enough rigidity to allow stack bolts to be tightened to desired torque setting (25nm). Holes are cut out for stack compression bolts, electrolyte inlet and gas outlet ducts and for affixing current conductors.

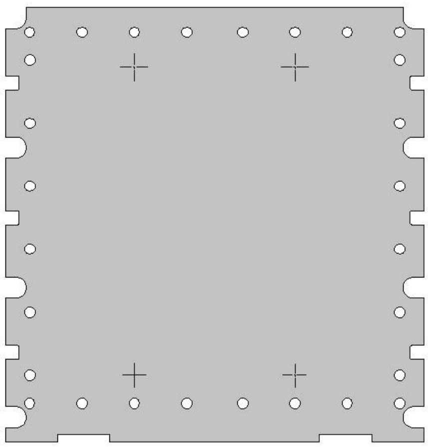


Figure 3. 10mm endplates

3. Spacers

The spacers create a gap for electrolyte and gas flow between the electrodes and the membrane. The outer dimension of the spacers are 510mm x 510mm and they are laser cut from 1.5mm butyl rubber or where available pre-cut to shape by the supplier of butyl rubber. Ideally the spacers should be symmetrical and therefore they can be prepared for use on the either side of the membrane to provide the division between hydrogen and oxygen gas.

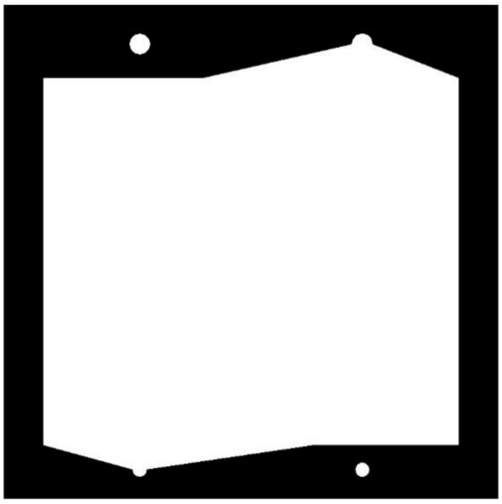


Figure 4. Butyl Spacers

4. Electrodes

The electrodes are laser-cut from 0.9mm 316L stainless steel, a small number are tabbed to allow for intermediate connection of conductors so that the stacks can be run at different voltages (i.e. multiples of 12V) and secondary devices can take a small amount of power from the stack for their operation (e.g. low voltage/power electrolyte circulation pumps).

Normal electrode: Tabbed electrode:

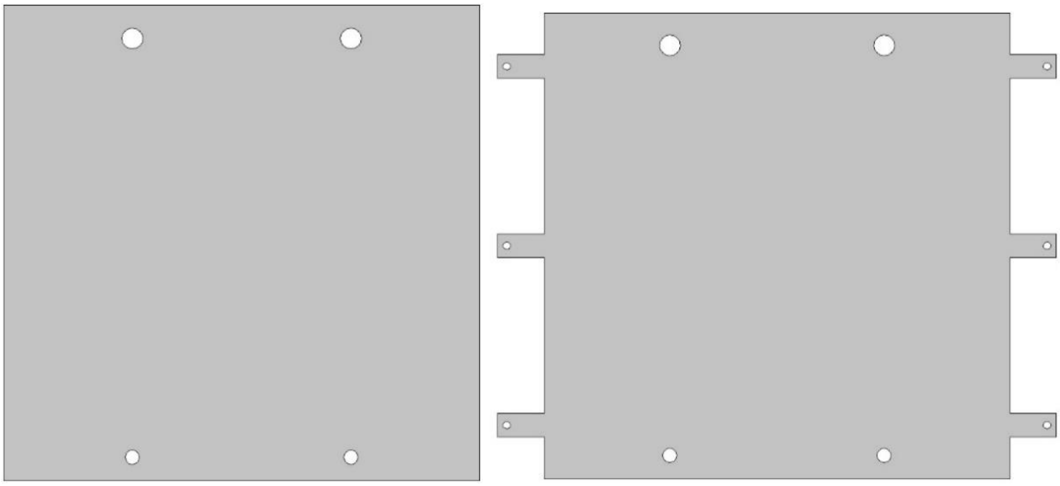


Figure 5. Electrodes (standard and tabbed)

The electrodes are 500mm x 500mm. the tabs are 50mm long and 25mm wide and positioned as shown in the drawing.

Electrode surface preparation

To enhance wetting of the stainless-steel electrodes, the surfaces can be roughened using an aqua blaster type device. To achieve the best result an even matt finish should be aimed for after blasting the 'active-area' of the electrode. When complete it will be obvious that the electrode surface is apparently hydrophilic with much reduced contact angle.

5. Membrane

The membrane used is the Agfa Zirfon Perl UTC500 and can be obtained from the manufacture pre-cut in the desired shape. The holes for electrolyte and gas flow can be added using the laser cutter or hole punch. If laser cutting, to ensure good repeatability, it is necessary to create a Jig in the laser cutter to assist with positioning the membrane each time one is cut. The jig can be cut from a piece of thin acrylic that is secured to the bed of the laser cutter so that it does not move during use. The membrane is slightly smaller than the spacer gaskets at 480mm x 480mm. This is done with the intention of avoiding leakage from the edges of the membrane. It is important to observe that the membrane is reinforced by the incorporation of a woven mesh sandwiched between layers of deposited polymer coating. Whilst this provides good mechanical strength to the Zirfon, it also provides a conduit for electrolyte to leak out of the stack edges. By making the membranes smaller they fall inside the area of the spacer gaskets and consequently the edges of the membrane are enclosed by the rubber of the gasket. An additional bead of sealant is used to enhance leak resistance and in the latest design the spacers and membranes are bonded using Cyanoacrylate adhesive as well as a bead of high grip and fill type adhesive (e.g. unibond 'sticks like sh*t').

6. Compression bolts (machine screws M10/stud)

28 x A2 stainless steel M10 hexagon-head full-thread bolts with corresponding nuts and 25mm diameter 'penny' washers are used to compress the stack and hold it together. The bolts pass through insulator plate and endplates that sandwich the inner stack of electrodes, spacers and membranes. In the 24V stack, bolts 120mm in length are adequate for the depth of 14 cells plus endplates. Longer bolts are required for 48V and the 96V require M10 threaded rod cut to length.

E3 Assembly of the stack.

Each stack is assembled on a dedicated wooden pallet that enable access to both top and bottom of the stack as it is assembled horizontally.

Figure 6. In this image the stack has been moved to the vertical position on the assembly support frame.

In place stack assembly

The electrolysers are assembled according to the following sequence:

1. An insulator plate is placed on the pallet, if there is a logo cut into the acrylic ensure that this will be in the correct orientation to be readable. The base of the stack, as it is assembled, should be the negative end. As standard all stacks are constructed such that the hydrogen exit port is on the left of the positive end and right on the negative end when viewed end on.
2. A 10mm endplate is positioned on the top of the insulator plate ensuring that the holes correspond to the position of those in the insulator plate. The endplates also act as the first (and final) electrode in the stack.

3. Place the first butyl spacer on the endplate. The electrolyte and gas holes should line up with those in the endplate. Alignment can be helped by using lengths of 20-22mm acrylic rod placed into the gas ports in the endplate against which all components can be aligned. The open side of the first spacer laid should be on the left, the hydrogen exit port, on the negative end plate.
4. Place a piece of membrane on the spacer and again check that it aligns correctly with the 4 holes. Lift the edges and glue with Cyanocryalate adhesive.
5. Run a continuous bead of **Unibond** high grip and fill adhesive around the edge of the membrane (all 4 sides). This is essential to guard against excessive electrolyte leakage as it seals the permeable membrane edge.
6. Apply a continuous bead of Cyanocryalate along the top surface of the membrane bout 5-10mm from the edge. Place the second butyl spacer on top of the membrane taking care not to disturb the sealant and adhesive whilst positioning it. Ensure that all the edges align properly with the lower spacer.
7. Place the first electrode on the stack, ensure all holes align and the edges are square. Press down around the edges so that sealant is compressed.
8. Repeat steps 3 to 7 another 13 times (for a 24V stack) but on the 13^{th} occasion replace the electrode with the second end plate. Care should be taken through all steps that all holes align well and that the stack is square and central on the end plate and all edges are clean and well aligned. Remove excess sealant as it leaks out at the edges of the stack using paper towel.
9. Place the second insulator plate on top of the endplate. Making sure that all holes are aligned and that the logo, if present, is clearly legible.

Assembly technique using Guide frame

An alternative method is to prepare a guide-frame or ‘jig’ and to first prepare the membrane and spacers as pre-glued units prior to assembly into a stack.

1. Prepare a jig:
    a. Laser cut a piece of 5mm thick acrylic 600mm x 600mm taking care to include holes corresponding to those in the membranes, spacer, and electrodes.
    b. These holes should be the correct size such that they will accommodate a short (~15mm) length of cylindrical acrylic rod.
2. Lay-up membrane and spacers:
    a. Installer the first spacer over the guide posts
    b. Run A bead of cyanoacrylate adhesive is run along the spacers top surface just inside where the edge of the membrane will sit such that when the membrane is laid down it will adhere to the surface of the spacer
    c. Run a bead of Unibond High adhesion and fill adhesive at the edge of the membrane
    d. Run a second bead of cyanoacrylate along the top surface of the membrane so that it is aligned with the first
    e. Lay the second spacer on top ensuring it is flipped over so that is the reverse of the first spacer, that its aligned on the posts and that the edges of both spacers are aligned and square
    f. Gently press down the second spacer so that it is evenly bonded to the other components
    g. Remove from the jig
    h. Optional: place in a large hot pressure to ensure that ‘unit’ is well and evenly bonded and that the adhesive ‘goes-off’.
3. Repeat unit assembly until there are enough units to build a stack.
4. Assembly of stack
    a. Place an insulator plate on the pallet, if there is a logo cut into the acrylic ensure that this will be in the correct orientation to be readable. The base of the stack, as it is assembled, should be the negative end. As standard all stacks are constructed such that the hydrogen exit port is on the left of the positive end and right on the negative end when viewed end on.

b. A 10mm endplate is positioned on the top of the insulator plate ensuring that the holes correspond to the position of those in the insulator plate. The endplates also act as the first (and final) electrode in the stack.
c. Place a membrane unit on the endplate ensuring that the holes are well aligned and that it sits square within the endplate.
d. Place an electrode on top of the unit again ensuring that the holes align and that it is square within the end plate
e. Repeat this step the required number of times according to the required voltage.
f. With the final cell, place the second 10mm endplate on top, again ensuring all components are correctly aligned.
g. Place the insulator plate on top of the end plate ensuring it has a positive legend showing and that the hydrogen port is on the left.

Bolting and compression of electrolysis stack

1. A total of 28 stainless steel bolts are required to compress the stack, each bolt hole should first be lined with 1 of 56 insulators, these are 10mm tubes of acrylic cut from 10mm acrylic sheet using the laser cutter. They are designed to fill the annulus created between the bolt shaft and the hole wall in the steel endplate. They should be sized such that they fit with a small amount of interference so that they resist dropping out of the hole.
2. Pass each of the 28 bolts through their respective holes in the stack, ensuring to install a 25mm washer.
3. Each bolt is then fitted at its end with a nut and a second 25mm washer. The end of the bolt thread should be dabbed with a small quantity of copper grease that will cover the thread as the nut is tightened. This is important as without lubricant, stainless nuts and bolts bind very easily under torque.
4. All bolts need to be tightened 'finger tight' and then, to ensure an even and stepwise compression of the stack, they should be tightened following the sequence below to the following torque settings.
   i. 5nm
   ii. 10nm
   iii. 15nm
   iv. 20nm
   v. 25nm (repeat this last step once on each of 3 consecutive days) or until no further compression is observed

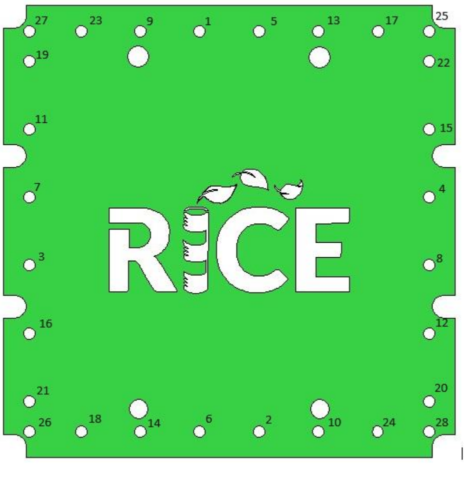


Figure 7. bolt torque pattern

E4 Preparation for stack installation

The stack is connected to electrolyte supply lines and gas output lines via the 4 connections provided on each face of the stack. The lower smaller connections are for the input of electrolyte and the upper larger diameter connections are for the gas and electrolyte output lines. The lower holes should be drilled and tapped for 3/8inch BSP thread and the upper for 1/2inch BSP thread. They can then be installed with compressed gas fittings for 12mm push nylon hose.

The stack will sit on its slower edge on an oil drum type containment bund.

For larger stacks, 48V and above, the diameter of these ports has been increased to ¾" for the smaller electrolyte inlet ports and 1" for the gas/electrolyte exit ports.

E5 Support Frame

A frame is required to support the various pieces of equipment that form the electrolyser unit. It has two functions; the first to supply a frame on which to mount items (equipment, pipework and instruments) so that they are safely supported and the second to elevate the main electrolyte reservoir to create a head of pressure to supply the electrolyser stack below. The following drawing illustrates the basic arrangement of the frame.

The red cross-members on the top of the frame illustrate where the IBC base sits and where it is secured. Single and double channel unistrut have different loading ratings per meter. At 2m single channel strut is rated for 2.168kN (221kg) and double channel strut 6.141kN (626.6kg) these figures increase exponentially as the span length reduces (data available at unistrut.co.uk). the design shown is therfore sufficent to support in excess of 1.1 tonne the maximum load of a full 1000L IBC.

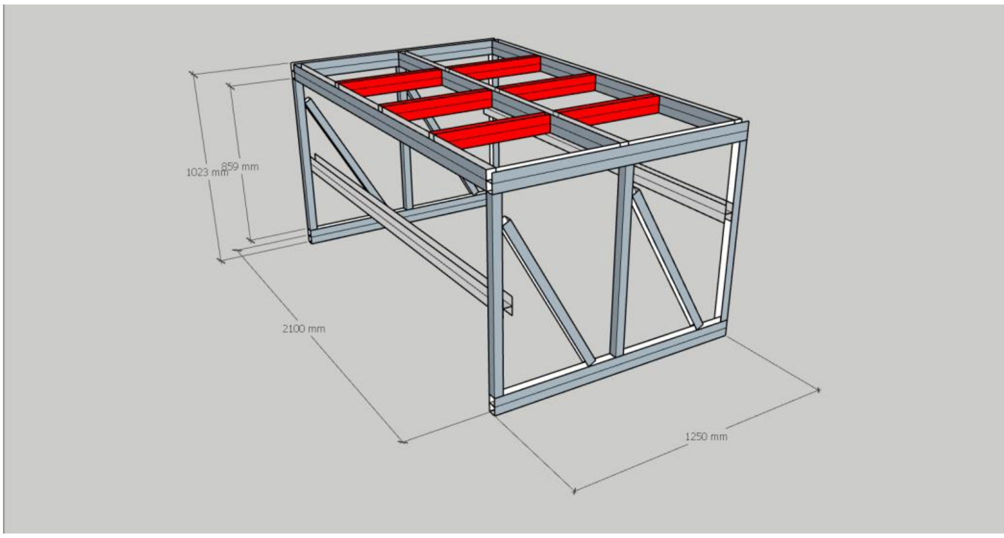
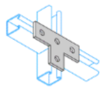
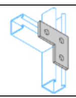
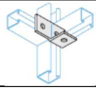
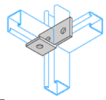
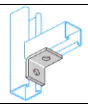
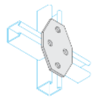
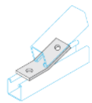
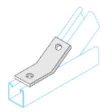


Figure 8. Support Frame (unistrut)

The frame is constructed from Unistrut or Unistrut type frame and brackets. The following table lists the 25 frame pieces and dimensions required to build the frame shown.

Item No.	Quantity	Description
001-005	5	2000mm double channel
006-009	4	1250mm double channel
010-015	6	859mm single channel
016-021	6	562mm Double channel
022-025	4	840mm single channel

Off the shelf unistrut type brackets, bolts and channel nuts are used to join the frame pieces. The following are required (plus 168 x 40mm M10 bolts, M10 channel nuts, M10 washer and spring washers):

Quantity	Part No.	Type	Image	fixings
14	P1031	Flat Tees		56
8	P1036	Flat 90° corner		24
4	P1037	Angle		12
4	P1038	Angle		12
12	P1026	Angle		24
6	P1580	Delta cross fitting		24
4	P2101_P2103	30° angle		8
4	P1546_P2095_P2097	45° angle		8

E6 Assembly of a typical joint

Each bracket is fixed to the frame with a bolt that screws into a 'channel nut' (PNL10) designed to fit in the channel as shown in the figure below. The reliability of the fastening can be improved by use of a washer/spring washer setup to prevent bolts coming loose with vibration.

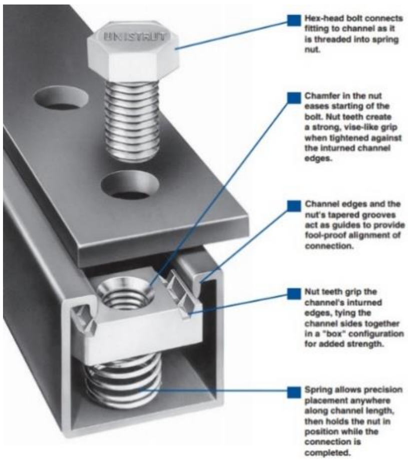


Figure 9. assembly method for unsitrut

E7 Separators

A significantly important unit operation in the electrolyser system, the separator functions as a means of separating the gases (oxygen and hydrogen) from the electrolyte being carried over from the electrolyser stack. It is a simple arrangement of some relatively large diameter pipework (110mm) a reducing tee and several reducers.

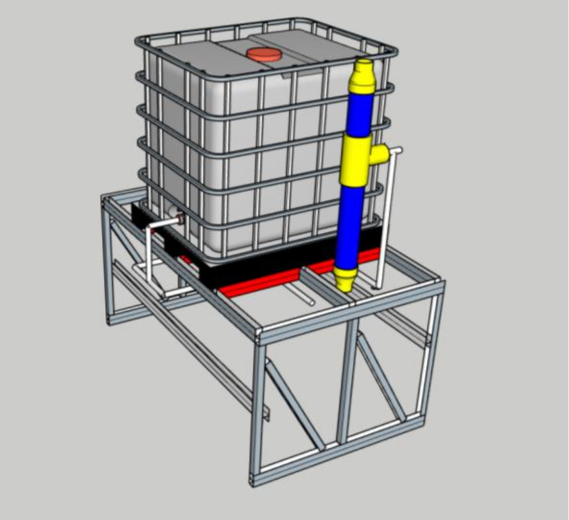


Figure 10.A separator and its position on the support frame

The gas/electrolyte stream enters via the side leg of the reducing tee. The tee is positioned towards the top of the separator so that the height of liquid in the separator is equivalent to that in the IBC such that the capacity for ‘dry’ hydrogen gas is only that volume above the tee and in the following low diameter pipeline. This head of liquid also creates a small pressure to drive the product gas downstream (~150mbar)

The separator is constructed from electrofusion pipework and fittings (plasson.co.uk, pipestock.co.uk, totalpipes.co.uk) using two 63mm x 110mm reducers, two lengths of 110mm OD MDPE pipe (1000mm and 200mm) connected by a reducing-tee 110mm x 63mm. The reducers connect to two short lengths of 63mm tube which in turn connect to two 63mmx32mm reducers and consecutively to two 32mm connecting pipe for returning unspent electrolyte to the main tank and gas to further downstream processing.

E8 Pipe work, valves, and tanks

The piping used to route hydrogen, oxygen and electrolyte around the electrolysis system is a combination of MDPE electrofusion tube and fittings and 25mm stainless-steel tube and compression fittings

In the appendix there is provided a P&ID providing the main constituents of the system and general connection with other components complete with a tabulated itinerary of all items (pipe, valves, equipment, etc).

E9 Tanks

3 types of tank are employed in the process system:

1. Electrolyte reservoir - Intermediate Bulk Container (IBC) (Fisher Direct). 1000L cubic tanks with a large fill port (manway) and a 3” drain port incorporating a butterfly valve. Adaptors are available to allow connection to the drain port using various electrofusion fittings. The walls of the container can be drilled and fitted with tank bulkhead adaptors, allowing for additional tank connections as required. These tanks are not pressure rated and are generally installed with a vent line, or open top to avoid pressurisation.

2. Scrubber – A 100L, cylindrical tank is employed for scrubbing the product hydrogen gas from the electrolyser. Filled with clean water the gas is bubbled thorough the water such that carried over hydroxides will be absorbed, and the gas exiting will be clean. A small headspace is necessary in order to avoid the contents being driven the gas outlet. The tank opening has sufficient space for a gas inlet connection and gas exhaust port. An additional port is installed low down the side of the tank to allow renewal of the tank contents.

Figure 21. Scrubber

3. Rainwater storage - 1500L vertical tank (1.72m x 1.2m). Installed adjacent to a suitable building for rainwater collection with a conventional gutter down pipe rainwater diverter. At the base of the tank is a valve to allow water transfer to the electrolyte IBC (this can be automated) through use of small pump

Figure 22. Water Butt

E10 Valves

A range of valves are included in the process. In most cases these are manual isolation valves (ball, plug, butterfly or gate) that allow the user/operator to isolate key components from the process if required exchange or repair/maintenance of equipment. In some cases there are solenoid valves for where automation is required. Finally there are non-return vales to prevent reverse flow where it is undesirable. In this process the following valves are used:

Tank exit butterfly:  Details: 2” butterfly, HDPE	Non-return valve:  Details: 1”BSP, Stainless steel, minimum lift pressure 25mbar, 0-25bar
Stainless steel ball valve:  Details:1” BSP, stainless steel, 0-63bar	Double spigot ball valve:  Details: 25-32mm electrofusion fitting, Polypropylene, 0-16bar.
 Solenoid valve: Details: 25mm (1”) BSP, stainless steel, atex approved, 24V, EODM	Flash Back Arrestor:  Details: 1”, hydrogen suitable, opening pressure 45mbar

E11 Pumps

Two identical pumps are used for circulating the electrolyte from the main reservoir through the electrolyser and back to the reservoir via the gas/electrolyte separator. The pumps used are low power brushless DC centrifugal pumps that have non-metallic contact materials making them highly resistant to corrosion from Sodium Hydroxide. These pumps are designed for use in continuous operation situations so should exhibit long term reliability.

Specifications:

Voltage	5-12Vdc
Head	2.4m
Flow	4.3L/min
Max Power	48W
Max Temp	60°C

Figure 23. electrolyte circulation pump

E12 Electrical

Electrical requirements are filled by a specialist supplier designed and constructed control panel and related specified peripherals.

The following details the specification of the control panel as installed on the Vale and Hanson systems.

E13 Baseline system for all units

The control panel provides the following functionality:

- 1 x Isolator (full shutdown). Lockable this will allow maintenance personnel to work on and around the equipment at no risk of electric shock, being sprayed with pressurised caustic soda or continued hydrogen production
- 1 x Emergency stop, key reset (full shutdown) on outside of unit. Offering the same function as for the isolator but for emergency shutdown in the event of significant operational issues either on the unit or site wide.
- 1 x Electrolyte tank low level warning (auto shut down) + warning indicator
- 1 x Low voltage warning at <17V (auto shutdown) + warning lamp
- 1 x 230V Mains power disruption response (auto shut down)
- 1 x Low/high temp monitor (auto shutdown on exceeding limits) + warning lamp

Shut down triggers the following:

  - Break power connection between renewables and stack
  - Close solenoid valve on H2 outlet to Vale
  - Brake wind turbines where present

E14 Power supply from external source

Solar = 3.2kW   200 A

Wind = 1.2 kW (2 x turbines) 200 A (Short circuit to break the turbines.)

Power output to electrolyser

DC supply 300 A capability.

E15 Continuous monitoring, data logging

V and I across the electrolyser output against time

Three thermocouples against time.

- Electrolyte
- Stack

E16 Display

Current status.

V and I

Total KWh of energy input

Total H_2 output

Carbon equivalent

E17 Renewable power

The energy required to run the water splitter is acquired only from renewable sources for the units detailed in this document there are 2 sources used: wind and solar. Other sources considered are waste heat recovery using heat to power technologies.

E18 Wind turbines

Small domestic scale lantern-type wind turbines were acquired for the purpose of generating power from the wind at the sites where these systems will be deployed. The typical power output of these systems is up to 600W under optimum wind conditions. The wind turbine generators output in 3-phase and are supplied with a basic invertor that converts to 24V dc so can, in theory be used directly attached to a 24V stack. However, for safety and good practice the 3-phase output will be run through a control panel that will allow for safe isolation of the stack and a facility for electric braking so that the turbine can be stopped under zero load conditions.

Specification

Power output	600W
Voltage output	24V
Starting wind speed	2 m/s
Nominal wind speed	13 m/s
Survival speed:	45 m/s
Generator:	Three-phase AC permanent magnet
Blades:	5 x nylon fibre

Figure 24. Wind turbine

E19 Installation

The wind turbines are mounted on the corners of the shipping containers using custom built brackets. The corners of the container are the strongest part of their structure so represent the best place to mount anything substantial. The wind turbines are supplied only with a flange on the generator that allows the user to attach an appropriate mast. In this project a mast was constructed using a 3m length of 60.33mm OD 316 stainless steel tube with a 2.77mm wall thickness. A flange was machined and then welded to the end of the mast that mated with the corresponding generator flange. When attached to container the centre of the wind turbine was projected ~1m above the top of the container. Power were able to run through the centre of the mast tube exiting at a point convenient for connection to the Power Control cabinet.

E20 Solar Panels

Where space allows, solar panels can be installed for provision of power to the electrolysis system. These can be mounted at ground level or, to a limited extent, on the roof of the shipping container. The latter option is very much dependant on the size of the container used and since these containers can be custom built as small as 10ft (3m) long by 8.5ft (2.55m) wode this would limit the number of roof mountable panels to at most 4 with some potential for overhang. The solar panels (320W Polycrystalline Solar Photovoltaic Panel) purchased for the RICE project are manufactured and supplied by Ledkia. These panels offered the best overall value for a 3.2kW of solar power (based on a matrix of ten panels) but not necessarily the most efficient in terms of power output per unit area.

Specification (each panel):

Power output	320W
Voltage	24V
Dimensions	1962x992x35mm
Weight	22.1kg

E21 Ground installation

When positioning the solar panels on any horizontal surface (ground, flat roofs etc) it important that panels are tilted slightly towards the sun to maximise their solar potential. The optimal tilt for the UK is 34° however it is necessary to balance this with wind loading concerns. Solar panels can be mounted on simple frames or using the Renusol Console system as chosen in the rice project. The Renusol system uses a wedge-shaped plastic bucket that can be filled with ballast and to which the solar panels can attached using proprietary brackets. These can then be position wherever they are required without demanding further fixing. The bucket angles the panel at 15° so the solar is positioned such that it will no catch the wind, the bucket itself also acts to deflect air flow away from the underside of the solar panels.

E22 Deployment of containerised units

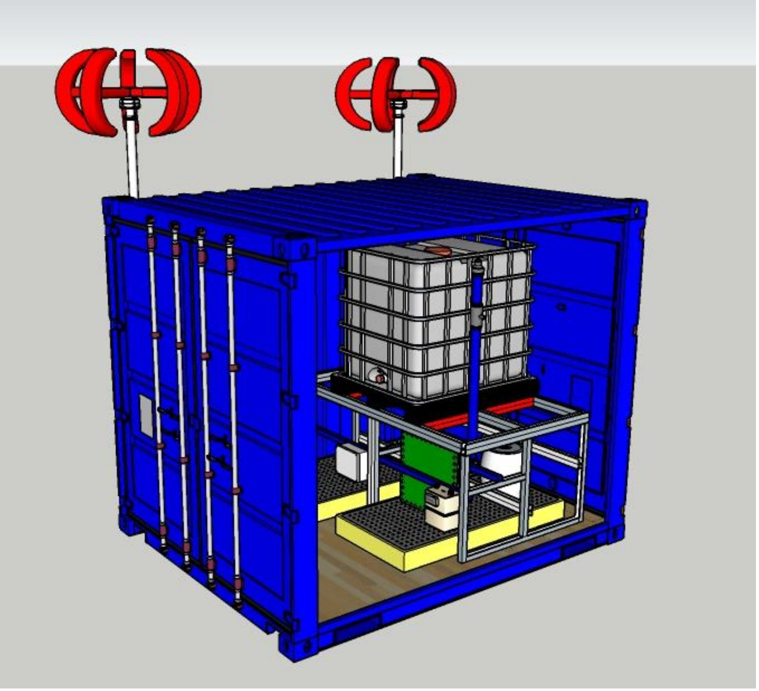


Figure 25. Final container installation

When complete all equipment internal and external to the container can be stored within a container for shipping. This should include the follow list of items

- Electrolyser stack
- Support frame
- Containment bunds
- Electrolyte tank IBC
- Wind turbines + masts*
- Solar panels*
- Solar panel support equipment*
- Separators
- Scrubber
- Connecting pipework
- Gas meter
- Ancillary gauges and control devices
- Power managements and control panel

(*optional items)

E23 The container

A 10-foot or 20-foot container provides a suitable housing for the equipment to protect it from the weather and to provide controlled access and safety for unpermitted personnel. Ideally the container used should be a 'high cube' as this offers improved head height. Although a 20ft container may prove to be much larger than necessary for the equipment used, it does offer a useful internal workspace, if it is required, for preparing electrolyte and assembling equipment or making repairs. The size of the container selected is dictated largely by the space available at the deployment location since there is not a significant amount of money to be saved by purchasing the smaller size – the 10ft containers are not standard, need to fabricated and do not necessarily meet the standards required for transport overseas on a container ship. The containers used in this project were obtained from Lion containers.

E24 Container ventilation

To ensure that no hydrogen gas can become trapped within the container during electrolyser operation additional vents were installed. These vents were positioned low on the sides of the container, close to ground level, to allow replacement air into the container and on the roof to allow hydrogen out. Hydrogen is highly buoyant in air so will rapidly rise to the top of the container and leave via any exit available, in fact it is likely that even without the vents hydrogen would not accumulate.

47mm hole saws were used to perforate the walls and roof of the container. The lower vent holes were then protected with small laser cut grills to guard against ingress of rodents an debris. The upper vents were fitted with 1.75" elbows, for additional weather protection, retained with a 1.75-1.5" reducer in combination with 2 washers cut from acrylic. All vents were sealed with additional silicone sealant to rain water ingress.

Figure 17 container roof vent assembly

E25 Safety signs

It is essential to have appropriate safety signs so that uninitiated personnel are aware of the hazards present inside and the vicinity of the container. Depending on where the equipment is deployed it might be necessary to have some or all the following: