

Article

IT-Enabled Sustainable Innovation and the Global Digital Divides

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Abstract: This article investigates the impact of information and communication technologies (ICTs), human capital, institutional settings, socio-economic, and environmental parameters on sustainable innovation (SI) using archival data for 127 economies from 2008 to 2017. We developed an econometrics research framework for investigating factors influencing SI on a global scale. We found that ICT variables, such as ICT access and ICT broadband network, positively influence sustainable innovation in conjunction with the socio-economic and political parameters. Despite differences among economies in terms of ICTs, socio-economic development, and educational attainment, ICTs are the significant drivers of sustainable innovation and economic growth. We observed a growing digital divide among nations within the context of the knowledge-based economy and the expansion of digital commerce, particularly in the least developed countries and Africa, a phenomenon impeding sustainable innovation growth. To the best of our knowledge, this is the first study that empirically investigates the global digital divide from sustainable innovation perspectives. The results of this study suggest that to tackle the digital divide issues, policymakers and educational institutes need to perform constructive educational reform in higher education curricula, particularly concerning STEM programs, which should reflect the necessary skills and competencies for deploying emergent technologies. In addition, ICT should be considered part of a country's critical infrastructure, particularly investment in the broadband networks regarded as the backbone of today's innovation.

Keywords: sustainable innovation; ICT; digital divide; e-commerce; FDI; STEM; civil liberty; economic freedom; institutional settings; intellectual capacity



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1. Introduction

The fourth industrial revolution, or industry 4.0, is marked by emergent technologies such as big data, cloud computing, quantum computing, artificial intelligence (AI), Internet of things (IoT), 5G, blockchain, machine-to-machine (M2M) communication, and business process automation, where the majority of products, processes, and services are digitized. This has drastically increased productivity, forcing major global economies to innovate and shift directions; thus, spawning knowledge-based economies. As defined by the Organization for Economic Co-operation and Development (OECD), knowledge-based economies describe an environment where technology and applying information are key factors in creating a competitive edge and maintaining some economic stability [1]. The strength of a knowledge-based economy is its ability to grow through innovation [2].

In this article, we use the definition of innovation as: “the intentional introduction and application within a role, group, or organization, of ideas, processes, products or procedures, new to the relevant unit of adoption, designed to significantly benefit the individual, the group, or wider society” [3] (p.10). Similarly, Carrillo-Hermosilla, Del Río, and Könnölä [4] define sustainable innovation (SI) as innovation that improves sustainability performance from the ecological, economic, and social perspectives. Other terms used for sustainable innovation are eco-innovation [5], and the green economy innovation

system. SI is defined as the process of developing new ideas, behavior, products, and techniques that contribute to a reduction in environmental burdens or ecologically specified sustainability targets [5]. Furthermore, innovation towards a sustainable society may be conceived as technological, social, and institutional [5]. In this context, government, society and market are driving forces towards the increase in both consumers' and companies' ecological awareness [6] (p. 76). Other scholars refer to smart government; its direct institutional support is to utilize environmentally friendly ICT, enhance work productivity, improve employees' work–life balance, and boost work processes' general efficiency [7].

From the perspective of sustainable development, innovation is viewed as capabilities of actors (firms, organizations, academic institutes, and individuals) in science and technology to innovate in products, processes, and services backed mainly through the intensity of investment in research and development (R&D) [8]. We are witnessing large divides among countries in technical skills, and R&D efforts and capacity [8]. As mentioned in [9], it is easy to assume that access to the digital economy is ubiquitous, and that online shopping is the natural evolution of commerce. E-commerce is only one facet of the evolving digital economy. Innovation, production, and sales are all being transformed by technological platforms, data analytics, artificial intelligence, 5G mobile networks, 3D printing, open science, connected and automated vehicles, smart agriculture, smart grids, e-health, emerging models for financial transactions, blockchains, cryptocurrency, digital wallets, and the Internet of things (IoT). However, the growth of e-commerce is not automatic, and the spread of its benefits not assured. The world economy has vastly different countries, each struggling from its challenges, some with decades of famine, others with astounding growth, and others with geopolitical tensions.

The main objective of this study is to investigate implications of ICT development, socio-economic development, intellectual capacities, institutional settings, and CO₂ emissions per GDPP in determining their impacts on predicting SI using global archival data for the period 2008–2017. Another objective is to investigate the existence of digital divides among countries and regions regarding broadband networks, classified as the backbone infrastructure for growth and development in the era of digital economies. These objectives are mapped to the following research questions:

RQ1: What is the impact of ICTs on the reduction of CO₂ emissions? Related to this question, what is the impact of ICTs on sustainable innovation and economic growth (RQ2)?

RQ3: What are the impacts of the intellectual capital, socio-economic and political settings on sustainable innovation?

RQ4: How to tackle the growing global digital divides from the perspectives of sustainable innovation?

As suggested by Higón, Gholami, and Shirazi [10], a macroeconomic approach examining the relationship between ICTs, socio-economic and political development, CO₂ emissions per capita, and innovation may help us answer these questions.

Thus, this study aggregates data for SI to determine these variables' significance. We conclude that although ICT is a critical factor in a country's ability to innovate, a basic level of the socio-economic, institutional environment, and intellectual capital must exist to maximize the potential of ICTs in increasing SI. Specifically, it makes recommendations for the least developed countries lagging behind the global trends. The article is organized as follows: Section 2 presents the literature review; Section 3 presents our research framework and the empirical model. In Section 4, we discuss our findings and the notion of digital divides from SI perspectives. Finally, discussions and conclusions are in Section 5.

2. Literature Review

2.1. ICT and SI

The rapid evolution of ICTs has changed business and communication among people. Billions of data are generated each day from businesses, medical records, media, governments, and individuals. It is estimated that 90 percent of the world's data has been created in the last two years, with both machines and humans contributing to its growth.

According to IDC [11], data will grow exponentially from around 33 zettabytes (A zettabyte is 10^{21} bytes) in 2018 to approximately 175 zettabytes by 2025; and nearly 30% of the world's data will need real-time processing; but more data does not translate into better information [12]. Mining data, and extracting, analyzing, and aggregating meaningful information to build desired knowledge, skills, and the ability to solve complex tasks has been welcomed by governments, policymakers, industry analysts, business strategists, and marketing pros as a new frontier for innovation, competition, and productivity [13]. Big data allows value to be created in new ways, and insights to be made on a large scale, impacting organizations, markets, and government-citizen relationships [12].

The underlying root of ICT's ability to affect SI is its purpose of facilitating information sharing, its impact on motivating humans to transfer knowledge [14–16], and the necessary tools to tackle environmental issues. For Hadad [17], changes in the paradigm of development of the global economy lead to an unprecedented increase in science value, as highly specialized knowledge and skills create SI and sustain competitive advantage [18]. In other words, since humans ultimately have to decide to share knowledge, the use of ICTs circumvents things like organizations with unfriendly sharing cultures. Thus, rather than facilitate the transfer of knowledge, ICTs offer four features and benefits to motivate individuals and organizations to share knowledge:

1. ICT removes barriers of distance, generation gaps, and social status.
2. It allows for storage of and access to data for multiple uses over an indefinite period.
3. Case-based reasoning tools provide the ability to iterate and continuously add to the knowledge available.
4. Information as meta-knowledge or information about the knowledge providers is embedded in the information.

These fundamental characteristics of ICT fulfill higher-level self-actualization needs, which include personal growth and achievement [19,20]. With ICT fulfilling this intrinsic human need, its ability to encourage and motivate individuals to transfer knowledge is strong [14,16,21]. For Van Laar et al. [22], although ICTs are a foundation for innovation, they do not create a knowledge-based economy. Innovation starts with people who can efficiently extract knowledge from the amount of available information and effectively apply such knowledge, both in their professional and personal lives.

With the right organizational approach, the benefits of ICT on productivity are evident [23–25]. Recent studies suggest a positive impact of ICT on innovation [26–29] in small to medium-sized enterprises (SMEs). In SMEs in the UK, ICT used in R&D departments produced high innovation levels in both process and product. Companies that maintained their websites were 8% more likely to innovate [27]. Gera and Gu [30] obtained similar results in their study of IT's effects on organizational innovation: the importance of ICT as a tool to stimulate innovation within SMEs is evident, given that favorable organizational structures and employee engagement exist. Specific advancements in ICT innovation, such as artificial intelligence, cloud computing, big data analytics, the Internet of things (IoT), m-banking, e-commerce, and more broadly, the Internet, are viewed as intrinsic factors that positively affect SI.

Although ICT is one source of global warming, generating more than 2% of global emissions and a major source of e-waste [10] it has offered several innovative tools to save energy. According to the Global e-Sustainability Initiative, ICT can reduce greenhouse gas (GHG) emissions by 20% by 2030 by helping companies and consumers more intelligently use energy. ICT applications can help increase agricultural crop yields by 30%, saving over 300 trillion liters of water, and 25 billion barrels of oil a year, generating USD 11 trillion in economic benefits by 2030 [31]. Also, as highlighted by UNCTAD's *Review of Maritime Transport Report* [32], the implementation of technical and operational measures for ships could increase efficiency and reduce the emissions rate by up to 75 percent. Moreover, the further reduction could be achieved by implementing innovative technologies (p. 89).

Motivated both by consumers, large ICT firms such as Google, Facebook, Adobe, IBM, and others are using renewable energy, mostly wind and solar [31]. In addition,

ICT is part of a country's critical infrastructure [8,9]. ICT creates synergies with other technologies such as biotechnology, nanotechnology, and advanced manufacturing as an enabling technology.

2.2. Broadband Networks, SI and the Paradigm of Economic Growth

Broadband networks are the backbone of IoT, the infrastructure for innovation, and the knowledge economy. Choi and Kim [33] argue that the future of a data eco-society relies on data intelligence and data science, the cornerstone for analyzing human life, business, and system operations to make better decisions. For UNCTAD [9], the number of IoT devices should grow from USD 15 billion in 2015 to USD 50 billion in 2020, with one third being computers, smartphones, televisions, and mobile devices. Valued at USD 656 billion in 2015, the market should reach USD 1.7 trillion in 2020 and between USD 3.9 and 11.1 trillion by 2025 [9] (p. 27). IoT drives the expansion of the Internet into the real world, due to the availability of inexpensive technologies that connect sensors, triggers, actuators, RFID tags, GPS locators, accelerometers, and more [34]. As an emerging innovation, IoT requires ubiquitous access to broadband networks to connect devices and objects and increase their efficiency by exploiting the potential of networking [35]. The next wave of innovation, 5G networks, is expected to provide connections for massive IoT, where billions of smart devices can be connected to the Internet [36], generating the next wave of big data resources. This broadband technology will have a marked impact on business and society, introducing new applications and opportunities for business models, markets, and essential public services delivery. They also offer several environmentally friendly applications, from monitoring the environment and animals to applications of e-agriculture. Thus, IoT requires new performance criteria such as energy efficiency, massive connectivity, security, trustworthiness, coverage of wireless communication, ultra-low latency, throughput, and ultra-reliability for a vast number of devices [35–37].

From the perspective of SI, wireless sensor technology provides energy-saving applications, such as smart grids, homes, buildings, metering, and renewable energy. For example, in transportation, the establishment of intelligent online transport systems integrated with GPS modules contributed to reducing traffic flows across cities. Software applications, such as video communication, e-commerce, and teleworking reduced the worldwide traveling of both people and goods, contributing to the reduction of greenhouse gas [38].

2.3. Human Capital and SI

With globalization and the decreased control of governments on business, innovation is positively affected. For Erkan [39], the freedoms endowed by the government (e.g., property rights, trade, and financial freedoms), directly affect citizens' ability to work and focus on innovating. However, economic freedoms favor companies [40] and labor freedom has the greatest impact on innovation. A study of Latin American countries found education provides the framework upon which economic freedom, FDI, and ICT build [41]. Lack of education inhibits innovation and slows the economy down. Education is a component of human capital, a determinant of economic growth. Thus, countries with high GDP and high levels of educational attainment have high capital stocks [42]. For UNCTAD [9], human capital relies on all levels of education, stimulates advanced cognitive skills, such as complex problem-solving, socio-behavioral skills, such as teamwork, and skill combinations, such as reasoning and self-efficacy [43]. It includes both the technical and managerial skills involved in innovation activities, from R&D, design and engineering to technology brokerage and networking [13]. Intellectual capital is the basis for innovation capability and sustainable economic competitiveness. The interactions among human capital, R&D, and ICT infrastructure are vital components of sustainable innovation [9].

2.4. Economic Freedom, FDI, and SI

The concept of economic freedom has been documented by economists and academics who have defined economic freedom and how it relates to macro-economic prosperity

and economic growth [44,45], and opportunistic factors, such as personal happiness [46]. For Gwartney and Lawson [47] four components of economic freedom are: (1) personal rather than collective choice, (2) voluntary exchange coordinated by markets, (3) freedom to enter and compete in markets, and (4) protection of persons and their property from aggression by others, including governments. For Dreher et al. [48], economic freedom is a precondition for foreign investors before investing in a country. Recent studies found that economic freedom is associated with the inflow of Foreign Direct Investment (FDI) [49–51]. Although economic freedom describes global freedoms on a per-country level, this study considers increasing the level of economic freedom as a paradigm from which to derive other parameters such as ICTs, FDI inflows, economic growth, and innovation. In other words, factors that lead to increased international economic freedom should increase innovation at “intra-national” levels.

Many nations have incentives to encourage FDI in their countries. Multiple benefits to local companies, the surrounding population, and the country make it an attractive policy. Several studies found a positive impact of FDI on innovation, R&D, and the global expansion of ICTs [51–54]. One often-discussed benefit of FDI is the influx of new technologies and sharing ideas fundamental to innovation [55]. Beyond the transfer of information, collaborative problem solving, and knowledge generation, FDI is an important driver of innovation [56]. Studies suggest that knowledge gathered through spillover is more valuable to innovation than the sharing of thoughts, ideas, and technologies [57]. For Taiwanese enterprises, FDI fundamentally altered best practices, ultimately forcing government policy to reflect the newly acquired knowledge of global standards from foreign partners [58,59].

However, the spillover effect of FDI into China was unique. Local innovators developed competing products and services to foreign ones, resulting in the accelerated growth of knowledge [60]. Studies by Cheung and Lin [60], Fu [52], and Wang and Kafouros [61] found that FDI had drastically contributed to R&D and innovation capacities in China. For Cheung and Lin [60], the increased innovation capacities in China, in part, were associated with the level of FDI flows, which provided spillover channels such as reverse engineering, skilled labor turnover, demonstration effects, and supplier–customer relationships. The rise of FDI from developing and transitional economies is of specific relevance to low-income countries, and FDI became an important component of developing countries’ economic [62]. For example, developing countries in Asia with FDI inflows surpassed half a trillion dollars, remaining the world’s largest FDI recipient region [53]. Other regional studies suggest the reciprocal impact of FDI investments. For example, in addition to traditional FDI spillovers, Japanese firms found their FDIs in the US particularly useful in propelling their R&D sector [63]. Another indirect effect of FDI on innovation is that it forces companies and countries to find new ways to create competitive advantages. Tang and Hussler [64] argued that in the case of FDI flows into China; international companies began to lose their competitiveness in their production costs and even quality. This forced investing nations to shift their economies to become knowledge-based to create value [65]. In addition to FDI, other sources of external capital flow, particularly for developing countries, are concessional loans from international financial institutions, long-term commercial debts, aid, and remittances [66]. However, investigating such resources is beyond the scope of this study.

2.5. SI and CO₂ Emissions

Lubberink et al. [67] argue that SI responds to societal and environmental challenges that require the involvement of multiple stakeholders. SI considers social and environmental impacts, in addition to economic impact, as desirable innovation outcomes [67]. For Cascio and Montealegre [68], although digital innovation will continue to advance, technology is not enough. Fulfilling its potential requires leaders and decision-makers to recreate their organizations’ operation in a world of digital ubiquity. For Higón, Gholami, and Shirazi [10], CO₂ emissions are the base currency of global warming measures. Al-

though research mainly focused on emissions of other pollutants such as sulfur dioxide or nitrogen oxides, recent studies increasingly focus on carbon emissions.

One issue with measuring CO₂ (metric tons per capita) as a standalone variable is that it discriminates against countries with low population density. For example, Qatar will become the highest polluted economy, while countries such as China, India, and Iran with a high level of CO₂ emissions will go unnoticed. Thus, we used the econometric variable CO₂ per GDPP to tackle this issue. This econometric variable highlighted these countries as economies with high environmental pollutions, which otherwise went unnoticed. Most countries with high CO₂ emission/GDPP are in Asia, followed by South Africa and Egypt, and four eastern European countries (Ukraine, Russia, Bulgaria and Estonia). On the other hand, the 20 low CO₂ emissions performers include Switzerland and Scandinavian countries (Sweden, Norway, and Denmark; Table 1b). We know that environmental issues are a serious global concern and need extensive national and international efforts. Thus, Table 1 is instructive for lessons learned from other economies, rather than relaxing global issues that impact all nations.

Table 1. The average values of CO₂ emission per GDPP (2008–2017).

(a) High CO ₂ Emission/GDPP		(b) Low CO ₂ Emission/GDPP	
Mongolia	2.690958	Switzerland	0.058854
Trinidad and Tobago	1.849018	Sweden	0.078634
Ukraine	1.816396	Denmark	0.105314
Kazakhstan	1.779817	Rwanda	0.110082
Iran (I. R.)	1.471903	Norway	0.111517
South Africa	1.314536	Mali	0.112198
Belarus	1.124969	Uruguay	0.120387
Russian Federation	1.093554	Ireland	0.121051
Lesotho	1.025634	Malta	0.123077
Bahrain	0.973398	Hong Kong, China	0.126415
India	0.929597	France	0.141763
Oman	0.926816	United Kingdom	0.145570
Saudi Arabia	0.926701	Iceland	0.145655
Egypt	0.918451	Sudan	0.148973
Algeria	0.900062	Costa Rica	0.150810
Vietnam	0.879712	Paraguay	0.151200
Kuwait	0.856230	Luxembourg	0.152446
Bulgaria	0.841819	Panama	0.161824
Benin	0.811288	Austria	0.168985
Qatar	0.802793	Zambia	0.180893
China	0.796917	New Zealand	0.181094
Malaysia	0.795647	Finland	0.181652
Tajikistan	0.794244	Italy	0.186226
Mozambique	0.784163	Singapore	0.188144
Estonia	0.748789	Israel	0.197262

The table highlights that the world's largest per capita CO₂ emitters are the major oil-producing countries; this is particularly true for those with low populations [69]. Most are in the Middle East: In 2017, Qatar had the highest emissions at 49 tons (t) per capita, followed by Trinidad and Tobago (30 t); Kuwait (25 t); United Arab Emirates (25 t); Brunei (24 t); Bahrain (23 t) and Saudi Arabia (19 t). However, many major oil producers have a relatively small population meaning their total annual emissions are low. More populous countries with some of the highest per capita emissions are Australia (17 t), the United States (16.2 t), and Canada (15.6 t). These countries produce more than three times the global average, which in 2017 was 4.8 t.

2.6. Institutional Settings and SI

Recently, our lives have been affected by significant limitations on how we interact, work, travel, learn, and create value, and technology often came to the rescue, helping us mitigate or circumvent such limitations. Teleworking, teleconferencing, telemedicine, distance learning, and e-commerce became part of a “new normal” that is changing every day [70]. The acceleration impelled by the COVID-19 pandemic has not been limited to the use of digital tools and services. It prompted a significant “deepening” of how governments, businesses, and individuals consider ICT innovations, technology adoption, and digital transformation [70].

A widening digital divide also highlighted the gap between developed and developing nations, particularly least developed countries (LDCs). Related to e-government growth and public-sector engagement, they felled short of expectations. The notion of e-government does not solely depend on technology. The complexity of e-government evolved to include political, cultural, economic, social, and technical dimensions. Using ICTs to serve citizens more efficiently [71] is an area where digital technologies can generate broad-based gains [70]. Bringing all these aspects together is so complicated that it needs carefully planned strategies informed at local, national, and international contextual characteristics.

From the perspectives of SIs, governments can play a supportive role in creating an environment that quickly reacts to new developments. This includes a supportive innovation ecosystem through government-promoted R&D investments, promoting and facilitating ICT adoption, supporting patents and ecological initiatives, and enforcing competition, building out infrastructure, and having a clear ICT strategy [70,72–74]. Systemic changes in current technological, institutional, and social settings are needed to achieve long-term sustainability goals [75]. The authors argue that the way to advance delivery of SI policy is by promoting public/private institutional structures to enhance regulator/regulated relationships and stakeholder activities; and ensuring broad stakeholder participation, particularly from the innovation constituency [75]. However, other than developing strategically and economically viable novelty, innovation is understood as a latent need that has to be undertaken to contemplate social and environmental issues [6].

3. Research Framework and the Empirical Model

The literature regarding economic growth as measured by per capita GDP (GDPP), FDI, economic freedom, and ICTs indicate that their impact on innovation is substantial. However, these reports are limited by the metrics measuring innovation. Traditionally, they were measured by the number of patents filed, patents cited, and R&D investments. These indicators provided data-based foundations for empirical research for a somewhat intangible concept. Acs and Audretsch [76] discussed the inherent value of using patent filings and citations as a tool to measure innovation, and concluded that this metric, although not perfect, aptly explains innovative activity. Griliches [77] describes the patent data as resistant to change in the absence of relevant data. This consistency over an extensive period makes patent data a useful resource in studying innovation [77]. Similarly, patent citations is a measurable form of data that helps identify links between different knowledge sources. Although, this is not a clear-cut indication of innovation, it suggests that these patents provide a basis for further inventions and therefore affect innovation.

Despite its accessibility and breadth, challenges exist in using patent related data as a tool to assess innovation. As found by Carpenter and Narin [78], and Kurtossy et al. [79], it has limited usefulness beyond ‘developed’ nations, where patenting technology is an established process for countries such as USA, Germany, and Japan. Despite attempts to standardize patent laws and procedures globally, the value put on them by developing nations, the incentives given to firms and the openness of an economy all play a significant role in patent filings [80]. In Kenya, for example, the lack of financial and procedural support from the government made filing patents by local companies less effective [81],

while government policies, such as China's grant subsidies, increased patent filings in that country by 30% [82].

Furthermore, industries where patent technology is an integral part of company success—for example, pharmaceuticals—are likely to skew the data. For Arundel and Kabla [83], in European countries, pharmaceuticals, chemicals, machinery, and precision instruments are the only ones likely to patent a product or process. The pharmaceutical industry leads product patenting by 79.2% [83]. This does not mean that other firms are less innovative or less careful in protecting their innovations. Instead, apart from these industries, patents provide more disclosure [84], and often facilitate competitors' development of new products. Instead, Cohen et al. [85] determined that lead-time and secrecy [86] are more effective methods for companies to protect innovation and proprietary information. Consequently, innovation studies focused on the patent information must incorporate other estimating innovation methods, as outlined in the following framework.

Figure 1 illustrates our research framework for investigating factors influencing SI on a global scale. The research aims to determine the extent to which four pillars of sustainable development impact innovation to tackle a wide range of socio-economic and political environments with the help of ICTs. The framework contains four pillars affecting SI: institutional settings, socio-economic development, intellectual capacity, and environmental settings. The framework is a building block in the construction of SI and other new technologies. There are variables within each group, and associated historical data explained in the next section. This framework allows us to investigate how ICT expansion and other parameters influence innovation and sustainable economic growth from 2008 to 2017. Analyzing the global digital divide among countries and its impact on human development is part of this study.

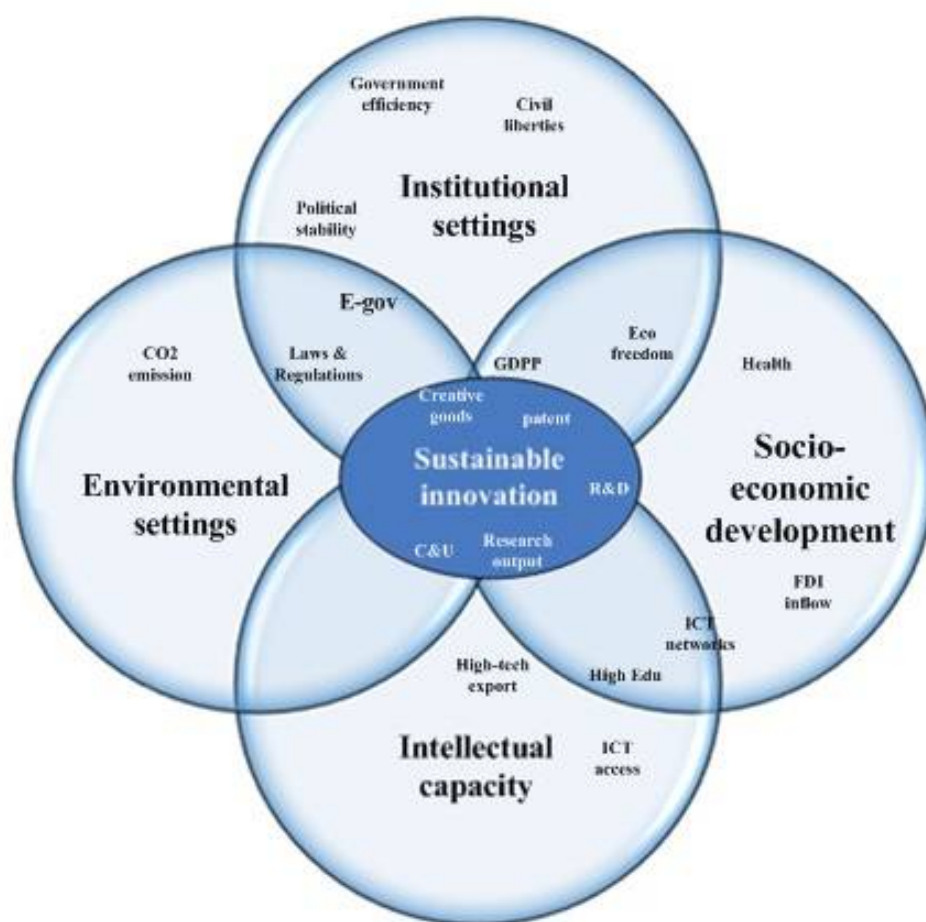


Figure 1. Conceptual framework.

For UNCTAD [62], there is a strong correlation between a country's ICT expansion, its income, human development level, and its citizens' educational attainment. UNCTAD [9] highlights the fact that there is a divide in R&D intensity (R&D intensity is the expenditure on R&D as a proportion of GDP) and the uneven distribution of researchers, particularly in developing countries. The report emphasizes the fact that increasing R&D intensity remains a long-term objective worldwide. R&D intensity in most developing countries is much lower than either the world average or developed countries. The technological gap is acute for the LDCs, where the intensity was 0.25 percent in 2014, and 0.41 percent in sub-Saharan Africa. This is alarming when we compare these facts with other countries such as the Republic of Korea (4.27 percent), Singapore (2.2 percent), and China (2.02 percent) [9]. Besides R&D gaps, ICT expansion, digitalization, and automation impose changes across many sectors, mainly manufacturing. Here, it plays a vital role in preparing the labor force with skills that complement technological advances. However, UNCTAD [9] highlights the "race between education and technology" [87], and the fact that "there are indications that educational institutes are not keeping pace with technological advances" (p. 42). To assess the independent variable's impact on SI (SI), we used data from 127 economies (we considered all economies with a complete set of data; please see Appendix A for a list of countries.) for the period 2008–2017. In the estimates, we used Stata software version 15.0.

3.1. Empirical Model

Based on the conceptual framework, we deployed ordinary least squares (OLS) regression and a general structural equation model called two-stage least squares (2SLS)/instrumental variable (IV). This model's main challenge is to find IV estimators correlated with the endogenous variable(s), but uncorrelated with the error term. In econometrics, these IVs are predetermined variables that use the instrument variables to find a consistent estimator of the coefficient for the original explanatory variable. We used the World Bank's political stability index as an instrument for the endogenous governmental variable (gov).

Our research model is the following reduced form Equation (1).

$$SI_{it} = \alpha + \omega intel_{it} + \phi inst_{it} + \Gamma eco_{it} + \Delta env_{it} + \varepsilon_{it} \quad (1)$$

where the subscripts refer to economy (i) and year (t); α is the intercept, and ε_{it} is the error term. We assume that the index of sustainable innovation (SI) depends on a number of ICT-based variables as in Equation (2).

$$\omega intel_{it} = \alpha + \beta_1 ictacc_{it} + \beta_2 ictnet_{it} + \beta_3 hightec_exp_{it} + e_{it} \quad (2)$$

Note that mobile broadband access as required by the emergent technologies, such as IoT, relies on the existence of national backbone infrastructure [37]. National backbone infrastructure and international Internet connectivity are key building blocks to drive broadband demand, access, and use. The amount of international Internet bandwidth available in a country provides crucial insights into the quality and speed of networks [37]. Additionally, international Internet bandwidth plays a vital role in delivering data-intensive applications and services through high-speed networks. While national fiber transmission networks are essential infrastructure for access to high-speed networks, information on bandwidth is also required to gauge the actual quality and speed available [37].

Equation (3) shows the institutional category of independent variables. The variable legal potentially belongs to this category, mainly as it is also an indication of government and institutional settings' quality. It is also associated with environmental settings as it measures the quality of environmental regulation in each economy.

$$\phi inst_{it} = \alpha + \gamma_1 cl_{it} + \gamma_2 gov_{it} + \gamma_3 legal_{it} + e_{it} \quad (3)$$

Equation (4) contains variables associated with socio—economic development in each nation. Another index associated with socio-economic development found in literature is

the UN's Human Development Index (HDI) [88–92]. We did not use this index because it contains GDP and educational information that may cause collinearity issues with other variables deployed in this study.

$$\Gamma_{eco_{it}} = \alpha + \delta_1 ecof_{it} + \delta_2 lnfdi_{it} + \delta_3 health_{it} + \delta_4 hingedu_{it} + e_{it} \quad (4)$$

Finally, the environmental pollutions measured by CO₂ emission per GDP (USD) are associated with Equation (5).

$$\Delta env_{it} = \alpha + \lambda_1 co2gdp_{it} + e_{it} \quad (5)$$

3.2. Data

The panel data consist of 127 economies from 2008 to 2017, resulting in an unbalanced panel with 1270 observations. We used different data sources, as explained below.

The economic freedom index is an average value of indicators from the Heritage Foundation and *Wall Street Journal* (HFWSJ). This construct was generated from 12 indicators—from property rights to financial freedom [93]. Economic Freedom (*ecof*) is an index between 1 and 100 (highest freedom) [94]. According to HFWSJ, within the context of economically free societies, governments allow labor, capital, and goods to move freely, and refrain from coercion or constraint of liberty beyond the extent necessary to protect and maintain liberty itself [95]. HFWSJ scores the level of economic freedom for each country on an annual basis. Economic freedom is important for countries because countries with more economic freedom experience much smaller economic crises and can recover to pre-crisis GDP levels in a much shorter time [96].

The inflow FDI data in log format (variable *lnfdi*) was from the UNCTAD database. The higher education (*hingedu*) from the UNESCO Institute for Statistics (<http://uis.unesco.org/> (accessed on 22 September 2019)) is an average value of two indices: gross enrollment ratio in tertiary education, and graduates in science and engineering. The latter measures sectors associated with innovation. Formal education is not the only source of acquiring innovation knowledge. However, this format was setup due to the absence of other education sources, such as employee training or employees who achieved a higher level of knowledge and expertise as part of firms' R&D projects.

The government efficiency index (*gov*) comprises two components: government effectiveness index and e-government readiness index. The index of government effectiveness was from the World Bank database. The index varies from −2.5 (weak) to 2.5 (strong) governance performance but was converted to 100 as the highest level of efficiency and 0 as the lowest. The e-government readiness index from the UN database measures the electronic government efficiency when it comes to ICTs, and in particular, the case of innovation. According to UN [97], the e-government readiness index captures the scope and quality of online services, the status of telecommunication infrastructure, and existing human capacity. The civil liberty index (*cl*) was from Freedom House. This variable recalculated and transformed from its original value with the scale of 0–100 (100 = highest level of civil liberty). The political stability index was used as an instrument for our 2SLS regression. This variable (not shown in equations) is from the World Bank's public database. This index was transformed to 0–100 (100 = the highest level of political stability) to indicate peace and the absence of violence.

ICT data (ICT access and ICT network infrastructure) were from the International Telecommunication Union (ITU). ICT access (*ictacc*) comprises four indicators: number of fixed telephone lines, Internet users, mobile cell phone subscribers, and number of households with a computer per 100 inhabitants. ICT network (*ictnet*) consists of two indicators: fixed broadband infrastructure networks in a country and international Internet bandwidth (Mbit/s per capita). The high technology export (*hightec_exp*), and the inflow FDI data were from the UNCTAD database. These data are in millions of USD.

Variable health consists of life expectancy at birth for both sexes (years), maternal mortality ratio (deaths per 100,000 population), total fertility rate (children per women),

hospital beds (per 10,000 people), and total expenditure on health as percent of GDP. Data was from the World Health Organization's public database (who.int (accessed on 30 May 2020)).

Variable legal consists of two indices: regularity quality and rule of law from the World Banks' public database (databank.worldbank.org (accessed on 30 May 2020)). To emphasize the importance of the quality of regulations and the rule and law, we placed variable legal in this category, even though it contains measures associated with environmental regulations' quality. As mentioned by EPI (epi.yale.edu (accessed on 30 May 2020)), the regulatory quality captures perceptions of the government's ability to formulate and implement sound policies and regulations that permit and promote private sector development. This includes the quality of environmental regulations. The rule of law captures the extent to which agents have confidence in and abide by society's rules.

The dependent variable, SI (*SI*) is composed of indices such as total R&D personnel (per thousand labor force), number of researchers per thousand employees, R&D expenditure as percentage of GDP (UN database), creative goods and services (UNCTAD), number of resident patent applications (per million population) (World Intellectual Property Organization, WIPO), scientific and technical publications, and trademark applications from WIPO, INSEAD, and Cornell University dataset. An issue in harnessing sustainable innovation is intellectual property (IP) transactions: purchase, sale, assignment, and licensing of intellectual property rights (IPRs). As IPRs are associated with technical innovation, patents are particularly important. The standard rationale for the patent system is to provide incentives for innovation [9].

Finally, variable *co2gdpp* measured the environmental pollution in each country. This index provides the amount of CO₂ emission (metric tons per capita) divided by GDPP (USD). We collected this data from the Environmental Performance Index (EPI, epi.yale.edu (accessed on 30 May 2020)), and the World Bank's public database.

4. Findings

Column (1) and (2) of Table 2 depicts the results of OLS and 2SLS/IV regressions for the entire dataset, while columns (3) and (4) show the results for least developed countries (LDCs). We deployed a first-order linear regression model [98] containing the main effects of all predictor variables. For the whole sample, there is a strong relationship between the dependent variable (*SI*) and the independent variables that construct intellectual capacities (ICT access (*ictacc*), ICT network (*ictnet*), high technology exports (*hightec_exp*), and higher education (*highedu*)). Their impacts are statistically significant at 0.01. It highlights the important roles of higher education on sustainable development, including the role of science and technology (SandT), in promoting innovation [99]. For Liu et al. [21], China has transformed itself from a planning to a market-oriented economy over three decades and has sustained a long period of rapid economic growth, to which the contributions from innovation in SandT have become important. Science and technology's role in economic development occurred after World War II. There has been a shift of focus from universities and technological sectors toward all parts of the economy to impact the innovation process [21,100].

However, variable *co2gdpp* shows a negative but statistically significant impact on *SI* (corr = −0.1897). The mutual relationships between these variables also show that *SI* is able to reduce CO₂ emissions caused by economic activities as measured by GDP regressions per capita.

Table 2. OLS and 2SLS/IV results (2008–2017).

SI	Whole Sample		LDCs	
	(1) OLS	(2) 2SLS/IV	(3) OLS	(4) 2SLS/IV
co2gdpp	−1.046 ** (−2.82)	−0.917 ** (−2.39)	−2.803 (−1.71)	−1.781 (−1.04)
ictnet	0.604 *** (11.43)	0.597 *** (11.27)	0.273 (1.89)	0.282 (1.91)
ictacc	0.0209 *** (4.86)	0.0189 *** (4.36)	0.0510 *** (3.94)	0.0503 *** (3.89)
hightec_exp	0.0491 *** (3.64)	0.0441 *** (3.25)	−0.0224 (−0.66)	−0.0248 (−0.74)
highedu	−0.606 *** (−6.90)	−0.590 *** (−6.38)	0.484 (1.80)	0.495 (1.83)
gov	0.186 *** (14.29)	0.235 *** (14.31)	0.237 (1.19)	0.248 (1.65)
cl	0.214 *** (4.87)	0.171 *** (3.78)	−0.129 (−1.19)	−0.144 (−1.28)
legal	0.191 *** (3.78)	0.207 *** (4.09)	−0.131 (−0.90)	−0.131 (−0.91)
lnfdi	0.162 *** (3.22)	0.147 ** (2.89)	0.327 (1.14)	0.447 (1.55)
health	0.383 *** (6.67)	0.358 *** (6.19)	0.121 (1.32)	0.129 (1.38)
ecof	0.128 ** (2.77)	0.157 *** (3.36)	0.107 (0.67)	0.263 (1.57)
_cons	−23.31 *** (−4.60)	−21.53 *** (−4.23)	6.725 (0.44)	−0.570 (−0.04)
N	1270	1270	230	230
R-Square	0.8184	0.8178	0.224	0.260

Notes: OLS (1) and (3) are robust regressions. The table provides variable coefficients along with OLS t-values and 2SLS/IV z-values in parenthesis. ** $p < 0.01$, *** $p < 0.001$.

The results of OLS and 2SLS/IV (columns (1) and (2)) related to institutional settings (*cl*, *gov*, and *legal*) show statistically significant impacts of government efficiency index (*gov*) on sustainable development at 0.01. The results indicate governments' effectiveness in setting sound policies in conjunction with civil liberties (*cl*); the quality of laws and regulations (*legal*) plays an essential role in promoting SI. It also highlights that civil liberties and the rule of law, the quality of regulations, including environmental regulations, play significant roles in sustainable development. These variables together also highlight the institutional trust in safeguarding individuals and firms in SI: development-led innovation policies have the function of identifying constraints and restrictions in the transformation process towards a new technological paradigm, and as building blocks in the construction of other new technologies [74]. For Foxon, and Pearson [75], sustainable innovation approaches emphasize the importance of institutional factors in influencing innovation's rate and direction.

The last group addresses the variables associated with socio-economic development and their impacts on SI. In Table 2 (columns (1) and (2)), the *health* variable's quality of life has a statistically significant effect on SI at 0.01. As manifested by the UN's Sustainable Development Goals (SDGs), the focus is on plans where ICT and innovation have roles to play, including such indicators as health, education, and environment. An example of addressing health on SI is through the current pandemic. A range of health-related innovations were introduced to manage the current health crisis effectively. These include innovations in digital health, biotechnology, pharmaceutical research, agriculture, and food safety [13,101–109]. Variables such as *ecof* (Economic Freedom) and *lnfdi* (inflow FDI) have a significant impact on SI at 0.05. However, in 2SLS/IV regressions, the results show that *ecof* has a significant impact on SI at 0.01. The effect of economic freedom on innovation confirms earlier studies that for the economically free nations, the capabilities for innovation (e.g., financial innovation) increase (columns (1) and (2); Table 2), as performance deviates from aspiration. In contrast, for the least economically free nations, financial innovation, for example, decreases (columns (3) and (4)), as performance deviates from aspiration. Dreher et al. [48] mentioned that economic freedom is the precondition for globalization for foreign investors to invest in a country. This study also confirms earlier studies that inflow FDI has a positive and significant impact on innovation, and when FDI increases as technology absorption and innovation capacity increases [110–113].

The R^2 (OLS and 2SLS/IV) in Table 2 for the whole sample is 0.82, indicating that the explanatory variables explain 82% of the variation in the target variable (SI). The R^2 for the LDCs is 22.4% (column (3)) or 26% (column (4)), compared with the values for the whole sample. In the next section, we discuss the findings of LDCs.

To assess the instrument validity in the 2SLS/IV approach, the p for the Durbin [114] and Wu–Hausman [115] tests of overidentifying restrictions are in Table 3. In all regressions, the p of the Durbin and Wu–Hausman indicate that the instruments are valid. The null hypothesis of these tests is that the variable under consideration can be treated as exogenous. Both statistics are highly significant, so we reject the null hypothesis of exogeneity. As such, we treat the gov variable as endogenous, and this variable has a high adjusted R^2 (0.834), indicating its significance when it comes to instrumental variable political rights. The other issues concerning the data set were related to heteroskedasticity and autocorrelation. We used the Huber–White robust standard errors approach [116] to test our OLS regression model’s heteroskedasticity-consistent standard error estimators (e.g., Stata `vce(robust)` option). To test the same issue associated with 2SLS/IV, we used two models (Tables A2 and A3) as reported in Appendix B. Table A2 is based on Kleibergen’s [117] heteroskedasticity test. As Kleibergen [117] mentioned, this test is set up to evaluate the weak instrument robust score based on Lagrange Multiplier (LM) measures. It also tests for autocorrelation issues related to a time-series model. Table A3 in Appendix B is another heteroskedasticity test using the fitted values (e.g., $\hat{X} \cdot \hat{\beta}$). Both models assure that there are no heteroskedasticity or autocorrelation issues, as discussed above.

Table 3. Endogeneity test and IV restrictions.

Variable	R-sq.	Adjusted R-sq.	Partial R-sq.	F (2,1259)	Prob > F
gov	0.8357	0.8344	0.6749	1306.65	0.000
Durbin (Score) $\chi^2(1)$			32.1445 ($p = 0.000$)		
Wu-Hausman F (1,1259)			31.6181 ($p = 0.000$)		

Another issue relates to the multicollinearity among variables. For Lin, Foster, and Ungar [118], variable selection algorithms are designed to seek an estimate of β that minimizes the penalized sum of squared errors. Multicollinearity is often encountered in applied regression models and occurs when two or more predictor variables are correlated. High levels of multicollinearity may lead to large variances in the least-squares estimators of beta coefficients in the regression equation. The correlations between the predictor variables’ magnitude influence the variance inflation factor (VIF). In detecting multicollinearity, we examined the variance of inflation (VIF). VIF is determined by $VIF_i = \frac{1}{1-R_i^2}$, where the VIF for independent variable i is the reciprocal of the inverse of R^2 for the regression model. The literature offers unclear guidance about which values for VIF are too large, and how the researcher should respond [119]. However, the simulation results suggest that a small sample size and low R^2 interact with high collinearity to produces inaccurate regression coefficients [120]. This is not the case of this study as it includes 15,240 sample points, considered a large dataset.

As argued by Daoud [121], multicollinearity can be observed in the following cases: (i) large changes in the estimated coefficients when a variable is added or deleted; (ii) large differences in the coefficients when a data point is altered or dropped. Multicollinearity may be present if: (i) the algebraic signs of the estimated coefficients do not conform to the prior expectation; (ii) coefficients of variables that are expected to be important have large standard errors (small t -values). The latter points did not apply to this study. VIF values less than 5 are acceptable. While value 1 indicates no multicollinearity, values larger than 5 indicate high collinearity [121]. As shown in Table 4, the highest reported VIF score was 4.14 (*health*), and lowest score was 1.04 (*hightec_exp*) and the average was reported as 2.58 indicating low levels of multicollinearity [122].

Table 4. VIF values of variables.

Variable	VIF	1/VIF
health	4.14	0.241546
ecof	3.75	0.266667
cl	3.65	0.273973
highedu	3.18	0.314465
legal	3.04	0.328947
gov	2.79	0.358423
ictnet	2.26	0.442478
ictacc	2.18	0.458716
co2gdpp	1.18	0.847458
lnfdi	1.14	0.877193
hightec_exp	1.04	0.961538
Mean VIF	2.58	

4.1. Least Developed Countries

As revealed by ITU [37], out of 44 countries ranked as least developed countries (LDCs) or least connected countries (LCCs), 30 are in Africa, including the ten countries with the lowest rankings. Other LDCs are located in the Americas (one) and nine countries in Asia-Pacific. This study covers data for 23 LDCs (21 countries from Africa and two from Asia). In these countries, the availability and affordability of high-speed fixed-broadband services remain a challenge. A fixed-broadband plan with a minimum of 1GB of data per month corresponds, on average, to over 60 percent of GDP per capita. In addition, the offered broadband services in terms of speed and quality are usually lower quality [37].

In Table 2 (columns (3) and (4)), both OLS and 2SLS/IV report that ICT access (*ictacc*) in LDCs has a positive and statistically significant impact on SI. This is due to the expansion and the use of mobile cell phone [123,124] and internet access in LDCs during the ten years. On the other hand, high-speed ICT network (*ictnet*), as measured by fixed broadband networks and the international Internet bandwidth, is statistically insignificant at 0.05. Consequently, the export of high-tech products and services, as measured by *hightec_exp*, is impacted by low ICT access and ICT networks. Table 2 shows the statistically insignificant impact of *hightec_exp* on SI, indicating a growing digital divide compared to the rest of the world. In this context, despite slow progress on intellectual capacity, we witness a widening gap in higher education, including in the areas of science and technology. In Table 2, the *highedu* variable is statistically insignificant. Additionally, the socio-economic parameters such as health, economic freedom (*ecof*), and inflow FDI (*lnfdi*) are statistical insignificant. The same is true when it comes to the institutional and environmental settings and variables such as government effectiveness (*gov*), civil liberties (*cl*), *legal* and *co2gdpp*. These variables point out the inadequate quality of institutional arrangements, and the extent to which governments promote participation in SI through regulation and adhere to principles of civil liberties and the quality of the rule of law and regulations.

4.2. Digital Divide

Cater [125] argued that the least developed nations face enormous obstacles in reaching even the low development levels of other poor nations; our study's findings show that the same is true 33 years later. As discussed, the international Internet bandwidth per capita remains particularly low in the LDCs, suggesting that the lack of international connectivity remains a major bottleneck in the Internet infrastructure of these countries. The findings show that the share of bandwidth for these countries is less than 1%. In addition, there is a sharp digital divide with the rest of the world and the most developed ICT nations. Figure 2 compares the international internet bandwidth of LDCs with four other categories namely Middle East and North African (MENA), ICT developed nations, ICT frontrunners (ICT frontrunners are economies with very high performance in ICT access, ICT network, and innovation. These countries in alphabetic order include Australia,

Canada, Finland, France, Germany, Hong Kong (China), Korea Rep., Japan, Netherlands, Norway, Singapore, Sweden, Switzerland, UK, and the USA) and the rest of the world.

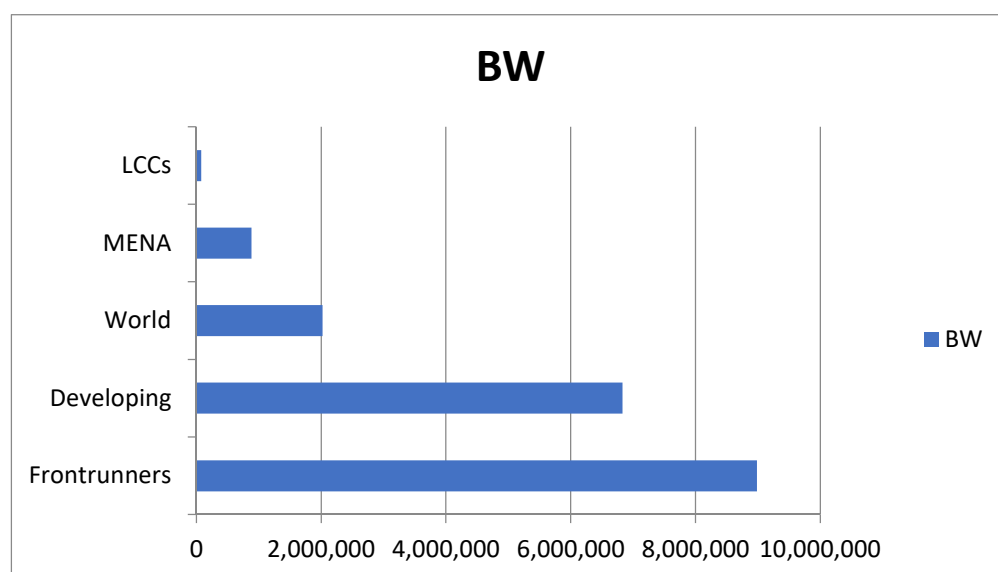


Figure 2. International Internet bandwidth, by region, 2008–2017.

Figure 3 shows the existence of a digital divide in LDCs and the rest of the world from the perspective of fixed broadband networks, and the combined fixed broadband and international Internet bandwidth (*ictnet*). While the world average of fixed broadband network was around 12.45 Mbit/s per capita, the share of this network for LDCs was around 0.30, compared the frontrunners' share of 33.80. This is important, because broadband networks are not only the backbone of today's IoT, but also the infrastructure for innovation, and the knowledge economy in general. According to OECD and WTO [126], high-speed affordable broadband access is essential for social and economic development. Technological advances in areas such as IoT and artificial intelligence, combined with hyper-connectivity, are leading to an increasing variety of services and applications that can serve economic, social, and entertainment needs [126].

For African countries and LDCs, the most significant innovation challenges relate to institutional settings and socio-economic developments. Access to ICT is critical to innovation. However, in countries like Nigeria, which do business in relatively well-defined and regulated industries, inflow FDI is necessary for ICT to continue to push innovation as it incentivizes knowledge sharing [127]. The findings show that the degree of FDI inflow into the host country is directly associated with existing economic freedom. Economic freedom increases the possibility of FDI inflows [49].

Nevertheless, a more detailed analysis of LDCs' data shows that besides ICT access, a significant factor in predicting a nation's innovation levels, the existing level of tertiary education is insignificant. According to UNCTDA [9], there is a wide gap between LDCs, African countries, and the rest of the world regarding the distribution of science, technology, engineering, and mathematics (STEM) graduates. Africa's STEM share is less than one percent compared to 29.2% for India and 26% for China. A holistic approach is required concerning the educational systems within STEM, as an essential factor for developing necessary skills and competencies in today's digital business marked by cognitive economies [128]. This approach should come from a collaboration among policy-makers educational, and training institutes through a constructive reform in curricula. Akcomak and Weel [129] suggested that the educational system builds large social capital within a country, directly affecting SI. As Van Deursen and Van Dijk [130] mentioned, the most consistent determinant in digital divide research is undoubtedly educational attainment. Van Dijk and Hacker [131] view the digital divide as a complex and dynamic phenomenon,

particularly when it comes to the diffusion of digital technology and innovation [132]. From the perspectives of ICTs and SI, the most consistent determinant in digital divide research is probably the educational level attained. From the viewpoint of today's networked society and information economy [133], people with a high level of education use more information [130] on a daily basis. Sustainable innovations play not only major roles in today's ICT-enabled knowledge economy [45], but managing knowledge is also associated with innovation [134].

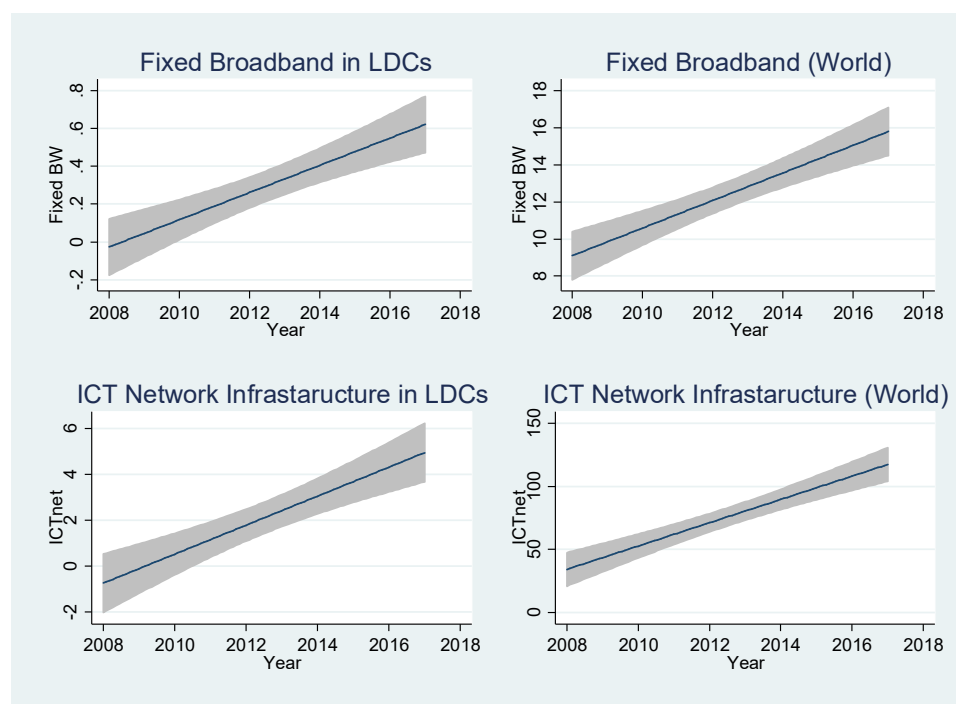


Figure 3. Digital divide in LDCs and the world.

As shown in Table 2 (columns (3) and (4)), there is no significant impact on the level of CO₂ emission per GDPP on sustainable innovation in LDCs. These countries contributed least to the emission of greenhouse gases, but they are most vulnerable to the effects of climate change [135]. Additionally, emergent “technologies hold the promise to revive productivity and make plentiful resources available to end poverty for good, enable more sustainable patterns of growth, and mitigate or even reverse decades of environmental degradation” [9] (p. 4). However, technological change and innovation need to be directed towards inclusive and sustainable outcomes, through a purposeful effort by governments, in collaboration with civil society, business, and academia. Governments are also falling behind using digital technologies efficiently for social impact [73]. Because innovation can be understood to flow from knowledge creation and applications [136], governments can do more to invest in innovative digital solutions to drive social impact. If policy-makers are not proactive technological disruption can entrench inequality, further marginalize the poor, and fuel reactionary movements against open societies and economies [8]. This is an alarming situation based on Africa’s population growth rate, including many LDCs. According to the World Bank, the population growth rate of 2.7% in Africa in 2017 is the highest population growth globally. In addition, the rapid expansion of urbanization, become a significant concern when it comes to air pollution, habitat destruction, and the loss of arable land. This is also an alarming situation when it comes to the quality of health care systems in LDCs. Our findings show that there is no statistical significance between variable *health* and sustainable innovation in LDCs.

The findings confirm studies by Dünser, Baelani, and Ganbold [137] who mention that given the high incidence of poverty, low literacy rates, unresolved and on-going civil

conflicts, mismanagement of resources, and deficits in socio-economic, political, and infrastructural conditions, general health care coverage remains a severe issue for many LDCs. They highlighted statistical figures that confirm the international health organizations' annual reports of low health care systems in these countries [137]. Additionally, regarding SI, patents, and knowledge economy, the primary obstacle to local innovation in developing countries and LDCs is not inadequate intellectual property rights (IPRs) protection, but lack of capabilities [8,9]. The creation of low-cost research activities is a high priority to stimulate the knowledge economy.

5. Concluding Remarks

Considering the rapid population growth and the finite nature of non-renewable resources, research studies focused on sustainable economic growth and innovation have become more and more critical for academics, practitioners, international and regional organizations, national authorities, and citizens alike [138]. A favorable environment for individuals, companies, and nations for sustainable innovation is fundamental to their ability to excel in the fourth industrial revolution. Historically, information and communication technologies (ICTs) provided the essential infrastructure, tools, and services to share and expedite the transfer of knowledge necessary for sustainable innovation.

Foreign direct investment (FDI), ICT, education, GDPP, and economic freedom are well documented for their direct positive effect and spillover effects on innovation. However, regarding sustainable innovation, we used Lubberink et al.'s [67] definition: an innovation that considers the intellectual capacities, socio-economic, and environmental impacts as desirable outcomes. Here environmentally sustainable product innovation involves developing products or technologies that are both market-oriented and cause minimal environmental impacts [6]. Following a literature review, we developed a conceptual framework to investigate the effects of these four categories on sustainable innovation. We analyzed the impacts of ICTs, intellectual capacities, institutional and environmental settings, and the progress of socio-economic development on sustainable innovation from archival data for 127 economies from 2008–2017. This study is among a few that investigate sustainable innovation on a global scale and the widening digital divide.

As shown in Table 2, despite the positive impacts of these variables, our study found an increasing digital divide between LDCs, those of developed countries, and the rest of the world. The digital divide impedes economic growth and innovation. To tackle the digital divide issues, we recommend constructive educational reforms and investment in national broadband networks by attracting FDI inflows in these countries. Besides, FDI inflows should consider implementing ICT broadband networks, as a backbone to innovative solutions and sustainable growth [139]. As emphasized in the literature, the latter requires political stability, respect for fundamental civil liberty, and the rule of law. The educational reform should emphasize practical, applied, and experimental learning approaches [9]. The reform in LDCs and African countries' curricula, particularly concerning STEM programs, should reflect the necessary skills and competencies for deploying emergent technologies. For deploying ICT infrastructure, policymakers and decision-makers should focus on incentives for attracting FDI flows, particularly in ICT broadband networks, as a backbone to innovative solutions and sustainable growth. Parallel with the above recommendations, the health of a growing population of African countries and especially LDCs requires deploying effective health care systems.

As emphasized by the UN's World Economic Situation and Prospects [140], structural challenges continue to hamper significant economic and social development progress. This includes a lack of infrastructure and public services, political instability, institutional deficiencies, and vulnerability to shocks from commodity revenue and extreme weather events. Finally, future studies on ICT innovation in developing countries should investigate the impacts from gender divide perspectives. It is claimed that the digital divide negatively influences women's participation in the digital sector, as women are seriously underrepresented in LDCs. For example, according to UNCTAD [9] there is a major gender

divide in mobile phone ownership, especially in South Asia, and in Internet use, especially in LDCs and sub-Saharan Africa, where the gap has widened since 2013.

Research Limitations/Implications

This study is limited to investigating digital divides from the perspectives of sustainable innovation. However, studies on ICT innovation in developing countries should also explore digital divides from gender perspectives, as the digital divide negatively influences women's participation in today's economic development as marked by ICTs.

Also, future studies should consider the deployment of ensemble techniques containing multiple models that are averaged in a particular manner to improve the accuracy of predictions [98].

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Appendix A

Table A1. Economies.

1	Albania	44	Guatemala	87	Norway
2	Algeria	45	Guinea	88	Oman
3	Argentina	46	Guyana	89	Pakistan
4	Armenia	47	Honduras	90	Panama
5	Australia	48	Hong Kong, China	91	Paraguay
6	Austria	49	Hungary	92	Peru
7	Bahrain	50	Iceland	93	Philippines
8	Bangladesh	51	India	94	Poland
9	Barbados	52	Indonesia	95	Portugal
10	Belarus	53	Iran	96	Qatar
11	Belgium	54	Ireland	97	Romania
12	Benin	55	Israel	98	Russia
13	Botswana	56	Italy	99	Rwanda
14	Brazil	57	Jamaica	100	Saudi Arabia
15	Bulgaria	58	Japan	101	Senegal
16	Burkina Faso	59	Jordan	102	Singapore
17	Cambodia	60	Kazakhstan	103	Slovak Republic
18	Cameroon	61	Kenya	104	Slovenia
19	Canada	62	Korea (Rep.)	105	South Africa
20	Chad	63	Kuwait	106	Spain
21	Chile	64	Latvia	107	Sri Lanka
22	China	65	Lebanon	108	Sudan
23	Colombia	66	Lesotho	109	Suriname
24	Costa Rica	67	Lithuania	110	Sweden

Table A1. *Cont.*

25	Côte d'Ivoire	68	Luxembourg	111	Switzerland
26	Croatia	69	Madagascar	112	Tajikistan
27	Cyprus	70	Malawi	113	Tanzania
28	Czech Republic	71	Malaysia	114	Thailand
29	Denmark	72	Mali	115	Togo
30	Dominican Rep.	73	Malta	116	Trinidad and Tobago
31	Ecuador	74	Mauritius	117	Tunisia
32	Egypt	75	Mexico	118	Turkey
33	El Salvador	76	Mongolia	119	Uganda
34	Estonia	77	Morocco	120	Ukraine
35	Ethiopia	78	Mozambique	121	United Arab Emirates
36	Fiji	79	Myanmar	122	United Kingdom
37	Finland	80	Namibia	123	United States
38	France	81	Nepal	124	Uruguay
39	Gambia	82	Netherlands	125	Vietnam
40	Georgia	83	New Zealand	126	Zambia
41	Germany	84	Nicaragua	127	Zimbabwe
42	Ghana	85	Niger		
43	Greece	86	Nigeria		

Appendix B**Table A2.** Sargan's homoskedastic and autocorrelation test. $LM = nR^2$.

Underidentification test (Kleibergen-Paap [141] rk LM statistic):		300.156
hi-sq(1) P-val =		0.0000
Weak identification test (Kleibergen-Paap [141] rk Wald F statistic):		817.105
Stock-Yogo [142] weak ID test		
critical values:		
10% maximal IV size		16.38
15% maximal IV size		8.96
20% maximal IV size		6.66
25% maximal IV size		5.53
Source: Stock-Yogo [142]. Reproduced by permission.		
NB: Critical values are for Cragg-Donald [143] F statistic and i.i.d. errors.		
Hansen J statistic (overidentification test of all instruments):		0.000
(equation exactly identified)		
Instrumented:		gov
Included instruments:		co2gdpp ictnet ictacc hightech_exp highedu cl legal lnfdi ecof hdi
Excluded instruments:		pr (political rights)

Note: According to Baum, Schaffer, and Stillman [144], the *ivreg2*, is an extension of Stata's 2SLS/IV module. It is designed under the assumption of conditional homoskedasticity, Hansen's J-statistic becomes Sargan's statistic. The J-statistic is consistent in the presence of heteroskedasticity and autocorrelation. Sargan's statistic is consistent if the disturbance is homoskedastic and (for AC-consistent estimation) if it is also autocorrelated. See also [98,145] for other model fit criteria.

Table A3. Stata IV heteroskedasticity test with fitted value (*ivhettest*).

IV heteroskedasticity test(s) using fitted value ($X\text{-hat} \cdot \beta\text{-hat}$)
Ho: Disturbance is homoskedastic
Pagan-Hall [146] general test statistic: 2.969 Chi-sq(1) <i>p</i> -value = 0.0849

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