Bridging the gap between circular economy and climate change mitigation policies through eco-innovations and Quintuple Helix Model

Abstract

Climate change represents an increasing threat to society and demands collaborative actions for changing technologies, production methods, and consumption. The concept of Circular Economy (CE) emerged aiming to increase the resource use efficiency and minimize resource inputs, waste and emissions generation. However, the contribution of CE eco-innovations to climate change mitigation goals, pushed by the Quintuple Helix Model (QHM) actors, is still unknown. This analytical review intends to fulfil this gap by investigating the main elements of the QHM that contribute to CE eco-innovations, namely companies, government, society, academia, and the natural environment. An analytical framework and theoretical propositions for future research are proposed. Eco-innovation technologies from energy, waste, transportation, construction and manufacturing sectors are discussed. Practical recommendations and implications for policymakers associated with CE and climate change policies and their interrelationship in terms of eco-innovations are also provided.

Keywords: Eco-innovation, Quintuple Helix Model, climate change, Circular Economy, energy efficiency, material efficiency, sustainability, sustainable business model.

1. Introduction

Climate change is becoming a main global concern. International environmental policies are seeking for a universal agreement to keep global warming below a critical threshold, that is, to limit temperature rise to 1.5ºC (IPCC, 2018). Achieving this goal implies a reduction of Greenhouse Gases (GHG) emissions (responsible for the 55% of global emissions), as well as a migration to a zero emissions economy by 2050. To implement such reductions, an annual decarbonisation rate of the energy system is estimated at 11.3%, which is seven times higher than the current rate (Ellen MacArthur Foundation, 2019). Nevertheless, climate change policy should not only focus on the reduction of GHG emissions from energy, but should also look to limit the quantity of raw materials used in manufacturing processes based on fossil fuels as they represent 45% of the total current GHG emissions (Behrens, 2016; IRP, 2019). In the context of world population growth, increase in demand for scarce resources and energy, and environmental burden, climate change policy becomes indispensable for creating a sustainable future society.

Thus, this situation requires reversing the trends by changing the traditional model of production and consumption to a more sustainable one. The conventional solutions for climate change mitigation, such as changing energy systems coupled with the use of renewable energy or the improvement of energy efficiency are not enough for meeting the challenge for 1.5ºC by 2050, as they only address a part of total emissions (IPCC, 2018). Solutions need also to focus on the growing demand for materials for producing goods and services that contribute to carbon emissions or land use. Some estimations point out that even with energy policies based on efficiency or zero-carbon energy sources, emissions from industry sector (steel, aluminium, cement, and plastic) will reach cumulatively 649 billion tonnes of CO_2 by 2100, and food production will have to meet the feeding needs of a 9 billion world population by 2050 (FAO, 2009; Ellen MacArthur Foundation, 2019; Fróna, Szenderák and Harangi-Rákos, 2019). This scenario indicates the complexity of the challenge ahead. It also raises the need to change the traditional production model based on linear flows, characterized by an excessive consumption of resources, generation of emissions and waste. This model compromises the needs of future generations as it is not sustainable in the long-term (Lüdeke-Freund, Gold and Bocken, 2018).

In search for new sustainable models, the Circular Economy (CE) concept arised from industrial ecology and received a lot of attention worldwide. The CE concept emerged as an alternative to the traditional production model by changing the way products are manufactured and consumed. Companies are increasingly adopting the CE principles in their business models to achieve more efficient use of resources and sustainable businesses (Lüdeke-Freund, et al., 2018; Kraus, Burtscher, Vallaster, and Angerer, 2018; Pieroni, McAloone, and Pigosso, 2019; Ferasso et al., 2020). CE is often considered a relevant enabler of Sustainable Development Goals (SDGs), including the 13th goal related to climate actions (Schroeder, Anggraeni, and Weber, 2019). As pointed in The Circular Gap Report, "the world can maximize chances of avoiding dangerous climate change by moving to a circular economy, thereby allowing societies to meet the goals of the Paris Agreement on Climate Action" (Circle Economy, 2019).

CE has received an increased interest by policy makers and has shaped many research agendas worldwide. For instance, the Chinese Government included the concept in its last Five Years Plans for National Economic and Social Development (Su, Heshmati, Geng and Yu, 2013; Zhou et al., 2014; Wu et al., 2014), and developed initiatives for promoting cleaner production, pollution prevention, and waste control. Some NGOs in the UK, such as Ellen MacArthur Foundation, have addressed the CE implementation (Ellen MacArthur Foundation, 2012, 2013, 2014). Other countries such as France, the Netherlands, Germany, Denmark, Sweden, South Korea, and Vietnam have developed conferences or initiatives regarding waste reduction or recycling programs related to the CE model. At the European level, the extended producer responsibility proposal, introduced by the EU Waste Directive in 2008, is the key strand for a CE, which is followed by the communication "Towards a Circular Economy: a zero-waste program for Europe". This report establishes measures to reduce the use of natural resources and the emissions of waste (European Commission, 2014a). Furthermore, the EU Action Plan for the CE package in 2015 seeks to boost European competitiveness through new business opportunities and innovative and circular means of production and consumption (European Commission, 2015). In 2019, a report on the implementation of the Circular Economy Action Plan reinforced the need for implanting the action plan (European Commission, 2019), and recently A New Circular Economy Plan for a Cleaner and More Competitive Europe (European Commission, 2020) was defined.

Incipient development of literature focusing on the relationship between CE and climate change is observed. Several studies revealed the potential positive effects of CE eco-innovations on climate change mitigation. These eco-innovations are related to the efficient use of materials and energy through recycling, remanufacturing or refurbishing (Murray, Skene, and Haynes, 2017; Ferasso et al., 2020). For example, the Waste Package of the European Commission estimated a potential reduction of 443 million tonnes of GHG between 2014 and 2030 (European Commission, 2014b). The Club of Rome's report estimated macroeconomic effects by moving towards a more CE in five countries (Finland, France, the Netherlands, Spain, and Sweden). The study was based on the introduction of three parallel actions: 25% more efficiency in the use of energy, 50% reduction in the use of fossil fuel in favour of renewable energy, and a more efficient use of materials. The estimations indicate that CO_2 emissions would decrease between 65% to 70% (Wijkman and Skånberg, 2016). Christis, Athanassiadis and Vercalstereren (2019) examine CE-climate change link from the consumption side at urban scale— since cities are considered major consumption nodes—trying to identify which CE strategies have mitigation potential.

The effects of CE transition were also examined in different industries. For example, the analysis of CE model adoption in three resource-intensive industries (transport, food & construction) showed that CO_2 emissions in the EU would decrease by 48% by 2030, and 83% by 2050, compared to 2012 levels (Ellen MacArthur Foundation, 2013). CE strategies applied in four energy-intensive sectors (cement, aluminium, steel & plastics) demonstrated a possible reduction of European emissions by 56% annually by 2050. At a global scale, emissions savings could reach 3.6 billion tonnes of CO_2 by year (Material Economics, 2018). A CE applied to the food industry could reduce emissions by 49%, or 5.6 billion tonnes of CO_2 (Ellen MacArthur Foundation, 2019). Recently, IRP (2020) assessed the contribution of material efficiency in residential buildings and light duty vehicles to GHG abatement strategies. The study concluded that material efficiency strategies can reduce emissions from materials and operational energy in housing by 40% by 2050 in G7 countries, and up to 70% in India and China; and in vehicles by 30-40% by 2050 in G7 countries, India and China.

Overall, improved resource efficiency and the reduction in use of raw materials become a key element of climate policy (Behrens, 2016; Rizos, Elkerbout and Egenhofer, 2019). They may be seen as effective strategies to reduce GHG emissions (Bijleveld, Bergsma and Nusselder, 2016). Moreover, the role of CE was highlighted to not only reduce direct emissions but also to avoid possible future obstacles in the deployment of new technologies (European Commission, 2018). In its New Circular Economy Action Plan, the European Commission (2020) called for a systematic approach to analysing the impact of circularity on climate change mitigation.

All these previous studies go toward the same direction. They demonstrate that the application of the CE may positively affect the mitigation of climate change. In addition, other studies pointed out that finer grained analyses are necessary as CE solutions do not always result in emissions reduction (Gallego-Schimdt, Chen, Sharmina, Mendoza, 2020). Thus, a case-by-case quantification is much needed. In addition, another study indicated that it is not sufficient to evaluate the potential of CE measures through production-based emissions only, and proposed a life cycle perspective in order to improve all life cycle stages (Deloitte, 2016). While most studies provided common insights that climate change and CE are intertwined, they mostly focused on the need to reduce resources use, to improve energy efficiency measures or production industries. Climate change is a complex problem that requires policy action, the participation of diverse stakeholders and the integration of knowledge from different disciplines and spheres of society (Grundel and

Dahlström, 2016).

This paper intends to address the call for a systematic perspective towards CE-climate change nexus. It aims to uncover the theoretical underpinnings and new rationales between CE and climate change mitigation policies by focusing on eco-innovations and the role of multiple stakeholders. It proposes an analytical framework and practical recommendations associated with CE and climate change policies taking into account their interrelationships. Eco-innovations are key drivers to tackle climate change and to carry out the transition from a linear to a circular system of production and consumption (de Jesus, Antunes, Santos and Mendoça 2018). We explore which eco-innovations contribute to both CE and climate change mitigation goals and emphasize that their development should be reinforced from public policy.

We frame our analysis within the Quintuple Helix Model (QHM) (Carayannis and Campbell, 2010; 2019; Barth, 2011; Carayannis, Barth and Campbell, 2012; Leydesdorff, 2012; Baccarne, Logghe, Schuurman and De Marez, 2016) by investigating the main elements, such as industry, government, society, academia, and natural environment, and their roles in driving eco-innovations. The transition to a zero emissions economy requires efforts from all the institutional agents (helix), by introducing CE principles in their climate agendas and strategies. In this context, we seek to answer the following research questions: *What are the commonalities between CE and climate change mitigation policies? How do QHM stakeholders contribute to CE and climate change mitigation?* and *Which CE eco-innovations benefit the achievement of climate change mitigation goals?*

The article is organized as follows. Section 2 proposes an analytical framework for CE and climate change nexus through QHM and eco-innovations. Section 3 reviews the literature on CE eco-innovations and presents the synergies with climate change. Finally, section 4 focuses on conclusions and recommendations.

2. Quintuple Helix Model: An analytical framework for CE and climate change nexus

2.1. Circular economy

CE model is a systemic response to environmental constraints intending to decouple economic growth from the consumption of finite resources through the resources efficiency (energy and materials) and the use of renewable energy (Ferasso et al., 2020; Johansson, and Henriksson, 2020). In this perspective, the introduction of *eco-innovations* aimed at the efficient use of raw materials and energy, the design of lasting products, the enhanced rates of recycling and reuse of materials, and the elimination of waste (Eco-Innovation Observatory, 2018). These advantages not only contribute to the reduction of emissions and thus, help to alleviate climate change issues, but they also benefit the entire society through energy and materials savings and job creation (Sulich, Rutkowska, and Popławski, 2020).

Resource conservation and the concept of industrial symbiosis are implicit in the CE model. This means that waste from one industry becomes useful feedstock for another with the maintenance of its quality and status as a resource (upcycling), transforming the notion of 'waste-as-a-problem' to 'waste-as-resource' (Okere et al., 2019). The model looks for a closed-loop supply chain with a double flow of materials: one from suppliers to manufacturers and, finally, to consumers, and a reverse one from used products from customers to companies for the recovery of their added value and the reuse of the whole product or a part of it (remanufacturing operation) (French and LaForge, 2006; Lieder and Rashid, 2016). Thus, resource consumption and discharges into the environment are reduced. The aim is to improve efficiency to reach a system free of waste and zero emissions (Yuan, Bi and Moriguichi, 2006). Overall, in CE, most of the products and components that are thrown away represent significant value and could be used again (Figure 1).

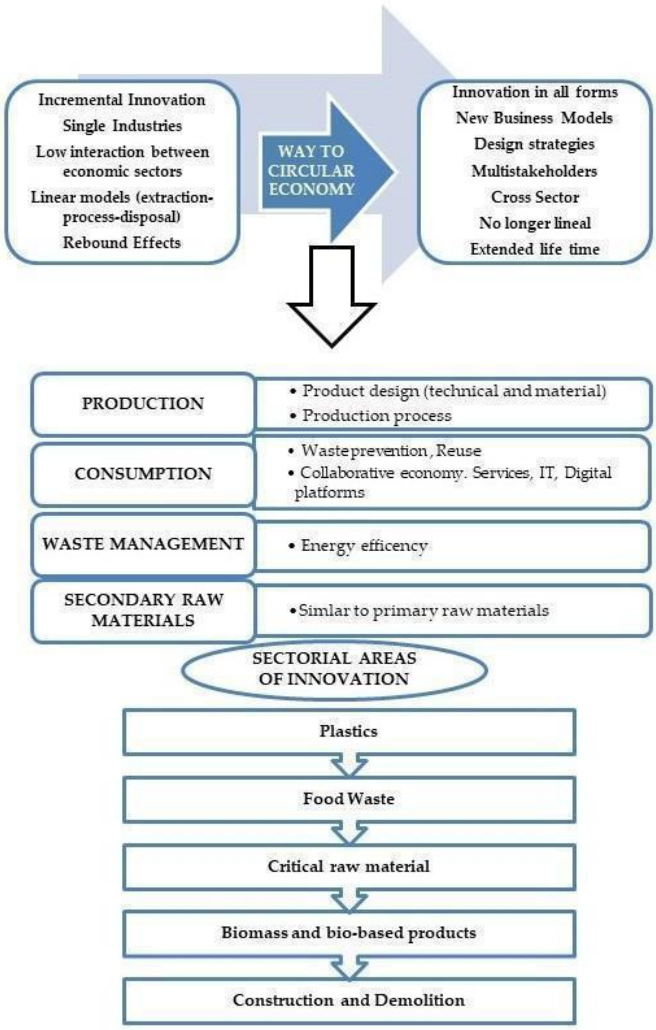

Figure 1. The Circular Economy model
Source: built based on Turécki (2016).

A closer look at the CE principles shows a connection between production (manufacturers), consumption (consumers), waste management and materials (secondary raw materials) with greater efficiency in energy and materials used. In the CE model, policy and legislation provide the theoretical support; however, the shift from a conceptual model to an operational one requires innovative transformations - technological, organizational or social - through the company's value chain (Ghisellini, Cialani and Ulgiati, 2016). CE requires the reduction of environmental impacts, such as waste and demand of virgin resources, and thereby the use of energy (European Environment Agency, 2015). Consequently, changes into business models oriented to sustainable manufacturing should be introduced, which implies environmental life-cycle analysis, technological innovations in products and processes as well as new social awareness (Kraus, Burtscher, Vallaster, and Angerer, 2018). Despite the CE advantages for the manufacture sector, in the practice not all companies have the same capacity to change their business models. CE knowledge is concentrated in big industries and dispersed across small and medium-size enterprises (SMEs) (Stahel, 2016; Christis, Athanassiadis and Vercalsteren (2019), Ferasso, et. al., 2020). CE transition may be a challenge for SMEs, as they have to overcome barriers such culture, market, supplier behaviour, administrative burdens and the lack of information, technical skills and finance (Rizos, Behrens, Kafveke, Hirschnitz-Garbers, Ioannu, 2015; Kirchherra, et al., 2018). Hence, it is valuable to create an innovation ecosystem in which other stakeholders such government, civil society and academic institutions collaborate to facilitate the transition to CE (Stahel, 2016; Whicher, Harris, Beverley, and Swiatek, 2018; Nascimento et al., 2019).

2.2. CE and climate change linkages

Climate change is a global issue which requires international cooperation for cutting greenhouse gases, keeping the global average temperature below 2ºC and trying to limit it to 1,5ºC. In this context, CE is an important driver for reaching these objectives which implies a transition to the model based on the interaction between process, environment, and economy (Ghisellini et al., 2016). In fact, a successful implementation of the policies and measures proposed by countries in order to reach 1.5ºC by 2030 may not be enough, therefore CE strategies may contribute to further reduction of emissions through innovative solutions enabling a sustainable pathway.

Climate neutrality requires big transformations of value chains across the economy and the intervention in the process of a wide range of different actors: industry, government, academia, and civil society. This participation is referred to as 'institutional capacity', that is, a commitment of different actors to deal with common issues (Murray, Skene and Haynes, 2017; Saavedra, Iritani, Pavan and Ometto, 2018).

In a similar way, the Triple Helix Model of innovation includes collaboration between institutional agents such as government, industry, and university, contributing to knowledge creation and systematic innovations (Etzkowitz and Zhou, 2006; Razak and White, 2015; Scalia, Barile, Saviano and Farioli, 2018). It has been shown that the transition to a CE is dependent on networked triple helix system actors targeting circular-based innovations (Barrie, Zawdie, and João, 2019). This model was reframed due to unsustainable growth and environmental problems. Initially, a fourth helix was included under the term 'civil society' (Quadruple Helix) aiming to define a more democratic policymaking processes to innovation (Ahonen and Hämäläinen, 2012; Ranga and Etzkowitz, 2013; Haschea, Hoglund and Linton, 2019). Further, given a necessity to search solutions to new environmental problems, a new helix was introduced to the model (Quintuple helix) that represents natural environmental concerns. It is conceptualized as a contextualization of the four helices of the quadruple helix (Baccarne, et al., 2016) and considered as a driver of knowledge generation and innovation (Carayannis, et al., 2012) that allows cooperation and the formation of synergies between economy, society and democracy (Litardi, and La Bara, 2020).

The model offers a coherence between all helices, from public institutions (top) to firms (bottom) looking for an equilibrium between the economy and environment and by including civil society. The interaction between different subsystems (educational, industrial, political, social and natural environment) of the QHM and the circulation of knowledge flows that act as inputs between them, promote innovations, create value and contribute to a sustainable future (Carayannis, et al., 2012; Carayannis and Campbell, 2019). Hence, initiatives that impulse innovation in each helix where public and private organizations interact seek to have a positive impact on all other subsystems and society as a whole and have a potential to create a favourable framework for sustainability.

A number of studies applied the model to explain the drivers of knowledge creation and innovation needed for preserving the environment, for generating green technologies (Laguna-Molina and Durán-Romero, 2017), and for solving problems and transforming society into a bioeconomy or CE (Grundel and Dahlström, 2016; Anttonen, Lammi and Mykänen, 2018). Specifically, Carayannis et al. (2012) applied QHM as a proposal for addressing the global warming challenge, considering that the knowledge source is the more important asset, and the continuous knowledge circulation stimulates new one. Yun and Liu (2019) considered that open innovation in each helix contributes to enrich sustainability.

Given the existing developments in the field, the QHM may be considered to be an appropriate framework to the case of climate change and the transition towards CE. Both climate change and CE require a trans-disciplinary approach, the participation of multiple stakeholders (Behrens, 2016) coupled with the development of innovation in each helix (Yun and Liu, 2019) (Figure 2).

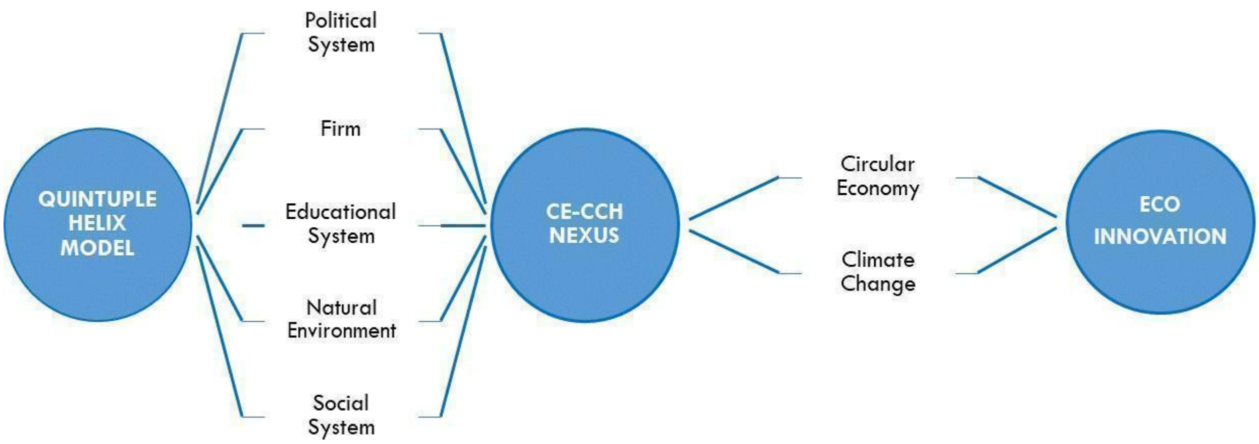

Figure 2. Analytical framework for Circular Economy and Climate Change Nexus through Quintuple Helix Model and Eco-innovation
Source: own elaboration.

CE arises in the middle of the innovation system and plays a key role in achieving decarbonisation objectives. It supposes a whole systemic perspective in which production and consumption are embedded in the wider biophysical environment and impacted by it. This implies that the decisions taken by the global and local institutional agents of the economy may help reduce environmental impacts (Figure 3).

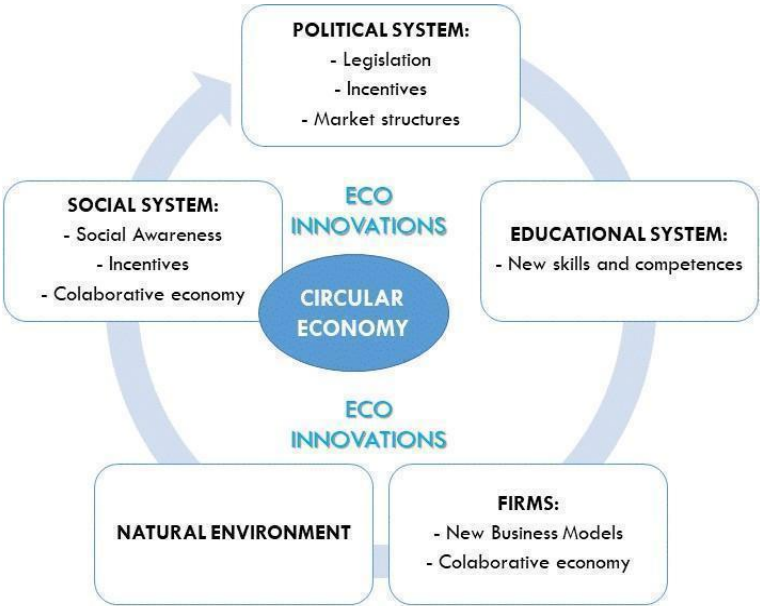

Figure 3. Relating the Quintuple Helix Model with the Circular Economy and eco-innovations
Source: own elaboration.

Eco-innovations are core drivers in the development of environmental technologies and the pathway for achieving integration and cooperation of different actors at macro, meso and micro levels that will also benefit to climate change mitigation objectives. This perspective about the importance of expanding the levels of analysis of climate change has been pointed out in a few studies about the role of context in shaping climate change (Flagg and Kirchhoff, 2018), the role of meso level policy networks (Ylä-Antila, et.al., 2018) or the contribution of tacit and explicit knowledge to climate change mitigation (Kaklauskas, et al., 2013).

Thus, QHM framework offers a tool for identifying the knowledge created in each helix that is exchanged between actors and generates eco-innovations related to the CE model, which are, in turn, suitable for climate change targets.

Government gives support through regulation that acts as 'push-and-pull' factors for implementation of eco-innovation within firms. It also develops and implements policies that reinforce the "reduce, reuse, recycle, and recovery" - the 4-Rs of CE model (Manickam and Duraisamy, 2019). The successful achievement of CE and climate change objectives also requires financial support and the creation of market signals in order to align producers and consumer interests. It is also necessary to implement incentives and instruments, firstly, for the effective development, acquisition, deployment and diffusion of eco-innovations and, secondly, for product design or recycling enabled innovation, and to motivate changes in social awareness.

Educational helix provides innovative responses to new social demands, supported by industry and government (Farré-Perdiguer, Sala-Rios and Torres-Solé, 2016). Schools should be engaged in learning relating to CE and climate change challenges to diffuse new skills and mindsets in new generations. University, as a strategic institution and creator of knowledge, should be one of the main agents to drive the process of CE by introducing the concept in the innovation process. It is important to strengthen collaboration among firms, universities and research centres where scientists contribute to the resolution of technical issues that arise in the innovation process through their experience and knowledge. Such collaboration is necessary between companies and universities to develop the research to address the real needs of climate change and CE (Durán-Romero and Urraca-Ruiz, 2015).

Although external stakeholders are determinant agents for the implementation of eco-innovations, CE models assume an enlarged firms' commitment. Firms should reinforce their responsibility as producers, rethink and change their business models. In this manner, they have to take into account the full product lifecycle from extraction to disposal and to take actions related to product design strategies, such as the choice of material inputs in the production process that will allow easier repair, reuse or recycle later, and the respect of the product life span. Such sustainable manufacturing or Resource Conservative Manufacturing paradigm proposes an alternative approach to linear production systems by looking for a dynamic interaction among business models, product design, supply chains, and customers (Asif, Bianchi, Rashid and Nicolescu, 2012; Rashid, Asif, Krajnik, and Nicolescu, 2013; Kim, Son, and Yoon, 2015). It also requires incentives, markets, and infrastructures as well as the development of other kinds of innovations such as Information and Communications Technology (ICT) crucial for the information exchange between businesses and consumers (Nascimento, et al., 2019).

Public social awareness in sustainable development has been increasing over the past years. The demand for a cleaner environment and the need for environmental protection have also served as drivers for eco-innovations in manufacturing and consumption patterns. As a consequence, changes are noticed in the manner in which manufacturing and consumption behave in relation to value given to products and materials, and to their consumption patterns and preferences, pushing for sustainable business models adopting a crucial role in the transition from linear to CE.

Overall, the QHM involves all the stakeholders that contribute to the transition to CE and to support the development of strategies leading to carbon neutrality that benefits all stakeholders. Considering this context, the first proposition of this study can be formulated as follows:

Proposition 1: The achievement of climate change mitigation objectives is facilitated by eco-innovations related to the CE model and the effective participation of multiple stakeholders of QHM.

3. CE eco-innovations: synergies with climate change

3.1. Eco-innovation

The eco-innovation concept refers to new or modified processes, techniques, systems, and products for avoiding or reducing environmental damage (Fussler and James, 1996; Arundel and Kemp, 2009). The transition from a linear economy to a CE implies changes in different stages of the production process and key sectors that are relevant for climate change mitigation. Within the CE framework, three strategies were set aiming the GHG emissions reduction: design out waste and pollution; keep products and materials in use; and regenerate natural systems (Ellen MacArthur Foundation, 2019). In these strategies, eco-innovations are key elements of the CE model, which drive the development of environmental technologies and the cooperation of different actors at macro, meso and micro levels.

Eco-innovation strategies allow the transition to sustainable economy, reducing environmental impacts, improving efficiency in the use of natural resources (Wysonkinska, 2016; Hojnik and Ruzzier, 2016), and contributing to climate change neutrality. The switch to a renewable energy supply and the improvement of energy efficiency in supply chains and business models will help to reduce emissions from the production of raw materials and waste generation (European Commission, 2011) and also to improve the profitability of companies (Hojnik and Ruzzier, 2016; Hart and Dowell, 2011). Table 1 summarizes the main characteristics, determinants, drivers, and potential benefits of eco-innovations.

Table 1. Literature review on eco-innovation

Key aspects	Approaches	Author(s)
Characteristics and determinants	Fundamental features and determinants	Beise and Rennings (2005); Arundel and Kemp (2009); Berkhout (2011); Kemp and Oltra (2011); Costantini and Mazzanti (2012); Borghesi, Costantini, Crespi and Mazzanti, (2013)
	Concerns on environmental management	Eiadat, Kelly, Roche and Eyadat (2008); Qi, Shen, Zeng and Jorge, (2010); Dibrell, Craig and Hansen (2011); Cheng and Timilsina, (2011)
	The relation between certain types of organizational innovations, such as environmental management systems and eco-innovations	Wagner (2008); Ziegler and Nogareda, (2009)
Eco-innovation drivers	Importance of demand-pull and technology-push instruments for the impulsion of environmental technologies	Costantini and Mazzanti (2012); Horbach, Rammer and Rennings, (2012)
	The role of external factors such as environmental regulation considered as a major driver of the emergence of eco-innovation in companies	Ashford, Ayers and Stone (1985); Porter and Van der Linde (1995); Shrivastava, (1995); Ulph and Ulph (1996); Jaffe, Peterson, Portney and Stavins, (1995); Rennings (2000); Jaffe, Newell and Stavins (2002); Rennings, Ziegler, Ankele and Hoffmann, (2006); Kemp and Pontoglio (2011); Agan, Acar and Borodin (2013); Ambec, Cohen, Elgie and Lanoie, (2013); Dechezlepretre and Sato (2017)
	Market-based instruments, such as economic incentives, as factors more effective than regulation	Rennings et al., (2006); Murovec, Erker and Prodan (2012)
	A mix between environmental regulation and market-based instruments	Oltra and Saint Jean (2009)
	Consumer pressure	Kemp and Pearson (2007); Horbach, (2008); Zeng et al., (2011); Doran and Ryan (2012); Chen, (2013)
Benefits provided by eco-innovations	Win-win situation, i.e., benefits both for the environment and for the companies	Porter (1991); Cainelli, Mazzanti and Montresor (2012)
	A better image (reputation) and lower costs for companies	Demirel and Kesidou (2011)
	New market opportunities	Shrivastava (1995); Clemens (2006); Kesidou and Demirel, (2012); Sarkar, (2013); Nidumolu, Prahalad and Rangaswami (2015)
	Higher levels of revenue per employee	Clemens (2006); Zeng et al., (2011)
	Improvement of sustainable performance	Boons Montalvo, Quist and Wagner, (2013)

Source: Own elaboration.

The literature on eco-innovation stressed its features as related to environmental management by companies, the role of regulation from external factors, as well as market and social pressures (de Jesus, Antunes, Santos, and Mendonça, 2018; 2019; Cainelli, D'Amato, and Mazzanti, 2020). Eco-innovations can provide numerous benefits for companies related to sustainability, reputation, and solutions for new market needs. Although the literature underlined conceptual aspects of eco-innovation, the understanding of how eco-innovations can contribute to the CE and climate change mitigation still needs to be uncovered.

The implementation of the CE model requires the participation of all stakeholders through knowledge generation that may serve as an incentive for the development of eco-innovations. Issues related to greater awareness of civil society, governmental incentives, and knowledge created at the education system act as driving forces of the CE model. However, the materialization of such forces substantially depends on the development of innovations. This implies the adoption of a consistent and holistic vision according to CE and climate change goals, and the involvement of eco-innovations in all production areas and at all stages of the product lifecycle, from the extraction of materials to waste disposal. This approach promotes best practices and minimizes waste through the such actions as reducing the quantity of materials required to deliver a particular service (light weighting); lengthening the products' life cycle (durability); reducing the use of energy and materials at the manufacturing and use phases (efficiency); reducing the use of materials that are hazardous or difficult to recycle in products and production processes (substitution); creating a market for secondary raw materials (recycles); designing products that are easier to recycle (eco-design); and facilitating the clustering of activities to prevent by-products from becoming waste (industrial symbiosis) (European Commission, 2014a). In addition, these practices also require companies to reconsider existing and develop new business models.

Within the climate change objectives, there has been a breakthrough in the development of activities related to climate change mitigation technologies and a lower carbon pathway (Dechezleprêtre, Glachant, Haščič, Johnstone and Ménière, 2011; Haščič, Johnstone, Watson and Kaminker, 2011; van Vuuren et al., 2018). Certain improvements have been achieved based on energy efficiency due to advanced technologies for generating electricity, or the carbon dioxide capture sequestration (CCS). Energy efficiency became a global warning issue and several actions targeting the de-carbonization of this industry is emphasizing the need of incorporating CCS as well as an increase in the use of renewable energy sources (Lausselet et al., 2017). In the past few years, due to a lack of progress in reaching temperature stabilization, several initiatives have attempted to accelerate eco-innovations for the development and application of low-carbon and cost-effective technologies (European Commission, 2016). Many of these technologies are end-of-pipe or have a preventive orientation, and, being aligned with CE principles, could offer opportunities to advance the transition to a CE model.

A number of studies provided empirical examination of the relationships among eco-innovation, climate change, and CE (e.g., de Jesus et al, 2018). Most of the research in the field has been based on the analysis of patent data for measuring the rate and flow of eco-innovations, estimating the knowledge concentration, and examining concrete topics related to mitigation measures (Durán-Romero and Urraca-Ruiz, 2015; Ferreira, Fernandes and Ferreira, 2020). Results show that the rate of innovation in climate change mitigation technology is higher in competitive technologies such as wind and solar power, biofuels, geothermal and hydro energy (OECD, 2010; Popp, 2011; Dechezleprêtre, Glachant and Ménière, 2012). It was also demonstrated that the technological know-how for pollution control resides primarily in firms in more developed countries, and that foreign direct investment constitutes the main channel for knowledge transfer. A perspective analysis based on the distribution of publications indicates that the research findings were primarily applied to the industrial and energy sectors, while green innovation has received scant attention in agricultural literature (García-Granero, Piedra-Muñoz, Galdeano-Gómez, 2018). Other topics focus on the relationship between innovation and pollution abatement cost expenditures (Brunnermeier and Cohen, 2003; Lanjouw and Moody 1996); the role of environmental regulation (Jaffe and Palmer, 1997; de Vries and Withagen, 2005; Popp, 2006; Johnstone, Haščič and Popp, 2010); the impact of energy prices (Popp, 2002; Dechezleprêtre, Glachant and Ménière, 2012); the importance of green certification schemes for the development of renewable energy (Johnstone, Haščič and Popp, 2010), the impact of intellectual property on the access to clean energy (Barton, 2007) or the role played by environmental protection agencies (Ball, Burt, de Vries and MacEachern, 2018).

Although the literature on eco-innovations has outlined the links between CE and climate change in general terms and the potential effects in terms of GHG emissions reductions of eco-innovations applied in different sectors, there is a lack of knowledge on the concrete technological innovations and their benefits for climate change mitigation. In the next section, we analyse climate change mitigation technologies and provide an overview of where reinforcements should be oriented in policy, legislation, as well as research and development (R&D).

3.2. Eco-innovations for climate change mitigation: practical examples and recommendations

For identification of taxonomy of environmental fields related to climate change mitigation, which potentially contribute to the reduction of GHG emissions, we used the OECD Thematic Areas of the Environmental Technologies (OECD, 2016). Each technological field is divided into different subgroups in order to obtain a more comprehensive and detailed view of environmental technology (Appendix). These thematic areas are based on the previous mapping of the existing and potential technologies for mitigating climate change developed by UNFCC (IPCC, 2007), that was also the basis of the IPC Green Inventory of the International Patent System[1]. We analyse how CE eco-innovations may change, improve or increase the climate change mitigation activities. We focus our analysis on different sectors, which were chosen because their economic growth is based on a high level of energy consumption and, consequently, a higher footprint.

[1] The “IPC Green Inventory” facilitates searches for patent information relating to Environmentally Sound Technologies as listed by the United Nations Framework Convention on Climate Change (UNFCCC).

3.2.1. Energy generation, transmission or distribution

This category is related to energy generation through renewable energy; technologies for the production from fuels of non-fossil origin; combustion technologies with mitigation potential; technologies for an efficient electrical power generation, transmission or distribution; enabling technologies in the energy sector; and capture, storage, sequestration or disposal of GHG.

Climate change is often described as an energy problem. Thus, the need to decouple economic growth and resources consumption and to mitigate climate change have led to the uptake of clean energy technologies (Witjes and Lozano, 2016), the implementation of comprehensive efficiency improvement strategies (energy consumption reduction), and the reduction of fossil-based fuels use (energy transition and energy savings through optimisation). These solutions are aimed to mitigate climate change, improve energy efficiency, and increase the use of renewable energy sources. Eco-innovations in energy are focused on the development and implementation of cleaner and low fossil-carbon energy sources that can produce power with much lower amounts of carbon emissions than conventional fossil fuels (Cai, Newth, Finnigan and Gunasekera, 2015; Gielen et al., 2019). These technologies are classified as:

- *Energy generation:* technologies through renewable energy sources, such as geothermal, hydro, solar and wind energy; technologies for manufacturing from non-fossil fuels origins, such as biofuels, biodiesel, bioethanol, biogas; and the production of fuel from waste or waste-to-energy (Okere, Ofodum, Azorji, and Nwosu, 2019). These energy sources are compatible with CE model only if they do not turn into toxic waste at the end of its usage, which will require the use of recycled materials, as in the case of some wind turbines;
- *Energy conservation:* also called saving technologies (e.g., storage of electrical energy, measurement of electric consumption, storage of thermal energy, low energy lighting, thermal building insulation, recovering mechanical energy) and energy efficiency, this energy is focusing on the generation of new solutions, technologies, products and services that contribute to the reduction of energy demand and consumption for manufacturing and other activities;
- *Combustion technologies:* alternative energy production-cycle combined, integrated gasification combined cycle, that have potential for CE and mitigation of GHG. This is the case of heat recovery from industrial units, using biomass as a source of renewable energy and a biological input in the CE model. A common example is the case of combined heat and power plants which provide electricity and heat by using biomass or incineration of waste. Yet, there is a controversy about their role in CE. Though this technology is considered as an effective means for closing the carbon loop as it reduces CO_2 emissions from fossil fuels, its use still requires large amounts of energy (Kočí, Rocha and Zakuciová, 2016);
- Technologies related to *capture, storage, and sequestration of CO_2* in geological formations (CCS) have been developed for mitigation purposes; however, there are different scientific positions on their application and role in CE. Although these technologies are considered to be effective means for closing the loop as they reduce CO_2 emissions from fossil fuels, their usage requires large amounts of energy (WEF,

2016). Moreover, CO_2 has been recently considered as a valuable resource rather than an industrial waste, which led to the development of new and innovative technology known as 'carbon capture, utilization, and storage' (CCUS) and 'carbon capture and utilization' (CCU) that contribute to a CE for carbon-based materials. According to Tcvetkov et al., (2019, p. 5), these technologies will require "(…) a revision of the attitude towards CO_2 and justify its role in the world economy (…) and the formation of the so-called CO_2 economy".

3.2.2. Wastewater treatment or waste management

This category involves the water pollution and wastewater treatment and solid waste management. Climate change is also associated with the high consumption of resources and materials. So, resource efficiency, which is in the core of CE, implies reducing waste generation, increasing waste recovery and waste usage as resources in the production process, contributing not only to the alleviation of planet footprint but also to the emissions reduction. Thus, technologies should be oriented towards the increase in the proportion of biological waste. Waste management innovations should consider the option of recovering materials (separate components and recycling) and energy (waste-to-energy) as better options rather than incineration and landfill. Recycling reduces the consumption of materials, and energy recovery contributes to the reduction of consumption of other resources, such as water and carbon emissions (Pan, Du, Huang, Liu and Chang, 2015). In the case of energy recovery, there are several possibilities: recovering from waste through organic materials or creating heat through the thermal treatment of non-recyclable waste. The last option is only recommendable if there is a guarantee of high value of maintenance. Technologies developed in this field are abatement technologies for waste management, pollution control, and wastewater treatment; however, not all of them are aligned with CE requirements. These are the cases of landfill technologies or the end-of-pipe technologies, such as sewage treatments systems and soil remediation, which are methods or treatments of surface water or groundwater, and technologies to restore degraded landscape. In recent years, bio-based alternatives have been developed, such as bioplastics based on sugar cane or corn, which are compatible with CE (Spierling, Venkatachalam, Behnsen, Herrmann and Endres, 2019).

Water is another crucial issue and a scarce resource requiring technological innovations for sustainable wastewater treatment and improvement of water efficiency, which, at the same time, contribute to energy consumption reduction. In this way, Jhansi and Mishra (2013) give an insight into the appropriate technology for treatment of wastewater. Within the CE model, wastewater treatment technologies present certain advantages. The separation of biodegradable substances allows obtaining substances — such as nitrogen and phosphorus— that are considered high valued non-renewable resources at the human life scale. These substances can be incorporated again in the cycle as fertilizers for agriculture. However, there are some drawbacks. First, decontamination implies a great amount of energy and materials. Although it could be balanced with the energy created from sewage sludge incineration, the global balance is negative. Second, the utilisation of sewage sludge is risky due to the high concentration of pollutants, such as heavy metals, that may contaminate food chain and groundwater (Kočí, Rocha and Zakuciová., 2016).

3.2.3. Agriculture, livestock or agroalimentary industries

This category comprises agriculture and forestry sectors and subsectors. Connections between CE and climate change can be observed in the agriculture and forestry sectors, which have a large potential for the implementation of eco-innovations for climate change mitigation (Durán-Romero and Urraca-Ruiz, 2015). In the last few years, eco-innovations have been focused on the development of biocides, alternatives to replace the use of chemical pesticides and used in different economic sectors. Additionally, organic fertilizers, derived from wastewater or food waste, are known as recycled nutrients (recirculation of key nutrients), and are returned to soil as fertilizers, which reduce the need of other chemicals with greater environmental impacts and contribute to the reduction of emissions in these sectors. It was estimated that if food waste is cut by 50%, and 30% of nutrients are sourced from organic waste or wastewater, the emissions of the sector can be cut by 13% (Deloitte, 2016).

3.2.4. Transportation

The transportation category involves emissions abatement and fuel efficiency in transportation; and enabling technologies in transportation. In the case of transportation, eco-innovations have been directed to the development of technologies that reduce the use of fossil fuels and emissions and increase fuel efficiency or reduce the material intensity. One of the barriers to CE model is the utilization of incremental eco-innovations that combine conventional energy sources with renewable ones. Furthermore, there are synergies in the application of fuel cells and hydrogen technology to transportation. Hydrogen replaces oil and natural gas; however, its extraction is energy intensive. Thus, it would be compatible with CE principles only in the case of using renewable energy sources for its generation. In addition, it would not only require technological innovations but also changes in the business models such as car sharing or carpooling.

3.2.5. Construction

The construction category comprises the integration of renewable energy sources in buildings; energy efficiency in buildings; architectural or constructional elements improving the thermal performance of buildings; and enabling technologies in buildings. The construction industry is the among the largest consumers of raw materials and waste generators, which results in a significant loss of minerals, metals and organic materials. This industry is responsible for 25 to 40% of the global total contributing to the release of carbon dioxide, being at a third position in the most emitting GHG industries in the EU (WEF, 2016; Gallego-Schmid, Chen, Sharmina, and Mendoza, 2020). Moreover, this industry should be changed to a more sustainable one using closed-loop circular design principles along the value chain (companies, technology suppliers and building materials or equipment) aiming at a reduction of waste and emissions. In this case, recycling can contribute to a reduction of the total emissions of about 17%, and further product reuse strategies need to be implemented to reach more significant reduction - up to 34% (Deloitte, 2016). These are the reasons the EU Action Plan is focusing on the construction industry for introducing it into the CE, although literature on CE and climate change mitigation proved to be scarce (Gallego-Schmid, Chen, Sharmina, and Mendoza, 2020).

3.2.6. Goods manufacturing

The goods manufacturing category involves the metal processing; chemical industry; petrochemical industry; and processing of minerals.

The production or processing of goods, such as chemicals, petrochemicals or metal and mineral processing, is responsible for large amounts of CO_2. At present, environmental technologies are introduced in their production processes with a goal of transforming it to a more sustainable.

Considering the discussion on CE eco-innovations and cooperation of different actors contributing to climate change mitigation, the second proposition of this study is formulated as follows:

Proposition: The achievement of climate change mitigation objectives should benefit from applying CE principles in eco-innovations during a) every stage of the manufacturing process, b) the definition of cleaner energy sources and its cleaner consumption, c) the use of products along their life cycle stages, and d) the definition of technologies for recycling, reusing and recovering materials and reducing waste, wastewater and carbon emissions. CE eco-innovations at the micro-level will indirectly relate to climate change mitigation through involving changes at the meso and macro levels.

4. Concluding remarks

The objective of this paper was to uncover the theoretical underpinnings and new rationales between CE and climate change mitigation policies. For this aim, a QHM is proposed as an analytical framework in which multiple stakeholders are part of an innovation ecosystem and knowledge is exchanged contributing to the development of eco-innovations that facilitate both circular economy and mitigate climate change mitigation.

Eco-innovations features involve the efficient use of materials and energy in order to promote recycling, remanufacturing and refurbishing. The analytical review of literature allowed to reveal the roles of different QHM actors in CE transition and climate change mitigation, and to identify the concrete CE eco-innovations that facilitate the achievement of climate change mitigation objectives.

Companies need to consider eco-innovations for achieving cleaner production methods, introducing renewable energy sources, and changing consumer behaviour by influencing society consumption towards CE principles. Moreover, academia contributes to the transition to the CE model by improving knowledge and skills on this issue and conducting R&D, which requires support from governmental incentives and funding. Academia can contribute to this transition by researching how to implement and optimize the recycling, remanufacturing and refurbishing, discovering new raw materials with lower impacts into the natural environment, identifying ways of minimizing the use of virgin resources, and introducing new and cleaner production methods targeting zero waste emissions.

When aiming at CE and climate change mitigation, the priorities of policymakers should first address highly resource intensive and polluting industries. Policies must be directed toward the tracking of energy consumption, the controlling of wastewater/waste generation while monitoring the natural environment impacts caused by agriculture and land/forestry use, construction industry, and goods manufacturing. In the context of ongoing concerns about environmental pressures and climate change, the reinforcement of CE and climate change mitigation policies is of paramount importance. This includes the implementation of measures in order to accelerate the transition to a CE model, which emphasizes resource efficiency in the context of a world with finite resources, and to achieve the climate targets. The role of QHM stakeholders is crucial in supporting this transition by the collaborative actions of companies, academia, government, and society to minimize natural environment impacts.

In the case of climate change, efforts have been mainly oriented to the development of eco-innovations for the mitigation of GHG emissions. Additionally, in recent years, a change in the economic model has been claimed in proposals, such as achieving a low carbon economy, green economy, or CE model, in which resource efficiency is a crucial element. Technologies aimed at climate change mitigation that could also contribute to the transition to the CE are being developed. However, the results of this study show that these technologies alone are still insufficient as they mainly focus on technical changes and require excessive energy consumption to be implemented. Some gaps related to energy efficiency, the use of materials and material recycling should still be overcome.

Governments have approved legislation and designed policies in order to emphasize the CE principles, which led to the introduction of technological eco-innovations. Yet, there is a challenge of involving QHM stakeholders in CE. Government has to establish incentives for both businesses and consumers; companies have to rethink and change their business models (industrial symbiosis, remanufacturing or product-service systems - PSS) along with setting strategic goals to close the circle loops, and to achieve greater levels of materials and energy use efficiency. It likewise implies the development of new and radical CE eco-innovations and increasing social awareness aiming to change consumer and producer behaviours towards a more collaborative economy.

Our study provides the following contributions to the literature.

First, we presented the links between CE and climate change by examining the five actors of the QHM. By identifying the role of CE in achieving climate goals, we identified the need for a regenerative and integrative model, in which natural systems are self-renewed with the aim of reactivating ecological processes damaged or over-exploited by human actions (Morseletto, 2020). This integrative model is derived from the Cradle to Cradle framework based on biological and technical closed-loop-cycles (Braungart, and McDonough, 1998). The need for a regenerative and integrative model is expressed due the finitude of fossil fuels, mineral resources and the growing demand of such resources. Thus, resources consumption directly impacts all QHM stakeholders, especially when considering the increasing population at global scales (Sauvé, Bernard, and Sloan, 2016).

To contribute to climate goals, this model must be more efficient in the use of resources, has to redesign business models or define new ones, focusing on changing consumption patterns, building resilience to climate change, and improving the quality of life of human beings. Based on the contribution of CE towards sustainability, this study proposes a framework for action to governments, businesses, and society.

Second, we analysed the connections between CE eco-innovations and climate change mitigation by addressing key technological innovations regarding sustainability across various resource-intensive industries. This study provides new insights on which eco-innovations may benefit the achievement of climate change mitigation goals. Implications for policymakers are addressed in order to reinforce the necessity to simultaneously consider CE and climate change goals, since literature showed their interrelatedness.

This paper is not without limitations. This theoretical piece is a pioneering study that combines CE eco-innovations, climate change mitigation and the QHM stakeholders to provide a more comprehensive model to address core sustainability issues. This preliminary study paves the road to future research that may be developed through theoretical approaches, starting by systematic literature reviews as suggested by Kraus et al. (2020). We also suggest greater theoretical exploration of each QHM stakeholder to identify specificities in each helix and how these may impact the overall model. Empirical studies are also needed to examine the mechanisms through which CE affects climate change, as well as to provide a finer grained analysis of the implementation of the recommendations. Further contributions from successful cases in implementing resource efficiency and GHG mitigation should be explored. Finally, we hope that this paper will encourage research addressing the specificities of developing countries based on energy/resources-intensive economies.

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Appendix. Climate change mitigation technologies

ENERGY GENERATION, TRANSMISSION OR DISTRIBUTION
Energy generation through renewable energy: Wind energy; Solar thermal energy; Solar photovoltaic (PV) energy; Solar thermal- PV hybrids; Geothermal energy; Marine energy; Hydro energy
Technologies for the production from fuels of non-fossil origin: Biofuels; Fuel from waste; Biodiesel; Bioethanol; Biogas
Combustion technologies with mitigation potential (e.g. using fossil fuels, biomass, waste, etc.): Technologies for improved output efficiency (combined heat and power, combined cycles, etc.); Technologies for improved input efficiency (efficient combustion or heat usage)
Technologies for an efficient electrical power generation, transmission or distribution: Superconducting electric elements or equipment; Smart grids as climate change mitigation technology in the energy generation sector
Enabling technologies in the energy sector: Energy Storage (batteries, capacitors, thermal storage, pressurized fluid storage, mechanical storage, pumped storage); Hydrogen technology; Fuel cells; Smart grids as enabling technology in the energy sector; High-voltage direct current transmission; Other energy conversion or management systems reducing greenhouse gas emissions
Capture, storage, sequestration or disposal of greenhouse gases: CO2 capture or Storage; Capture or disposal of GHG other than CO2
WASTEWATER TREATMENT OR WASTE MANAGEMENT
Water pollution and wastewater treatment: Water treatment, fertilizers from wastewater, incineration and energy recovery
Solid waste management: Waste collection, transportation, transfer or storage; Waste procession or separation; Landfill technologies aiming to mitigate methane emissions; Bio- organic fraction procession; Production of fertilizers from the organic fraction of waste or refuse; Reuse, recycling or recovery technologies (Dismantling or mechanical processing of waste for the recovery of materials during separation, disassembly, pre-processing or upgrading; Metal recycling; Disassembly of vehicles for recovery of salvageable parts; Construction or demolition waste; Glass recycling; Plastics recycling; Paper recycling; Fibre containing textile recycling; Rubber waste recycling; Recovery of polymers other than plastics or rubbers; Recovery of luminescent materials; Recovery of fats, fatty oils, fatty acids or other fatty substances; Recovery of tanning agents from leather; Recycling of wood or furniture waste; Packaging reuse or recycling; Recycling of waste of electrical or electronic equipment (WEEE); Recycling of batteries; Recycling of fuel cells; Nuclear fuel reprocessing; Reuse, recycling or recovery technologies cross-cutting to different types of waste)
AGRICULTURE, LIVESTOCK OR AGROALIMENTARY INDUSTRIES
Agriculture/Forestry: Forestry, soil improvement, alternative irrigation techniques (Agriculture machinery or equipment; Reduction of greenhouse gases (GHG) emissions in agriculture; Land use policy measures; Afforestation or reforestation; Livestock or poultry management; Fishing Food processing)
TRANSPORTATION
Emissions abatement and fuel efficiency in transportation: Road Transportation (Conventional vehicles -technologies specific based on internal combustion engine; Hybrid vehicles; Electric vehicles; Fuel efficiency-improving vehicle design (common to all road vehicles); Rail Transportation; Maritime transportation; Air transportation
Enabling technologies in transport: Electric vehicle charging; Application of fuel cell and hydrogen technology to transportation.
CONSTRUCTION
Integration of renewable energy sources in buildings

Energy Efficiency in buildings: Lighting; Heating, ventilation or air conditioning; Home appliances: Elevators, escalators and moving walkways; Information and communication technologies; End-use-side
Architectural or constructional elements improving the thermal performance of buildings
Enabling technologies in buildings
GOODS MANUFACTURING
Metal processing: Reducing of greenhouse gas (GHG) emissions; Process efficiency
Chemical Industry: General improvement of production process causing greenhouse gases (GHG) emissions
Petrochemical industry: Reduction of greenhouse gas (GHG) emissions during production processes; Bio-feedstock; Carbon capture or storage (CCS) specific to hydrogen production; Ethylene production
Processing of minerals: Production of cement; Cement grinding; Manufacturing or processing of sand or stone; Production or processing of lime; Glass production; Production of ceramic: materials or ceramic elements

Source: Own elaboration.