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Research article

Analysing the systemic implications of energy efficiency and circular economy strategies in the decarbonisation context

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Abstract: The Paris Agreement goals require a rapid and deep reduction in global greenhouse gas emissions. Recent studies have shown the large potential of circular economy to reduce global emissions by improving resource and material efficiency practices. However, most large-scale energy system and Integrated Assessment Models used for mitigation analysis typically ignore or do not adequately represent circular economy measures. This study aims to fill in this research gap by enhancing a leading global energy system model with a representation of energy efficiency and circular economy considerations. The scenario-based analysis offers an improved understanding of the potentials, costs and impacts of circular economy in the decarbonisation context. The study shows that enhanced energy efficiency and increased material circularity can reduce energy consumption in all sectors, but most importantly in the industrial sector. They can also reduce the required carbon price to achieve Paris goals and the dependence on expensive, immature, and risky technologies, like Carbon Capture and Storage. Circular economy measures should be properly integrated with broad climate policies to provide a holistic and self-consistent framework to deeply reduce carbon emissions.

Keywords: PROMETHEUS model; circular economy; energy and resource efficiency; demand-side mitigation options

1. Introduction

The consumption of materials forms one of the foundations of human development. The rapid growth of population and wealth resulted in a large increase in global material consumption from 27 to 90 billion tonnes per year in 1970–2018 period [1]. Materials including chemicals, food and structural materials are used to manufacture products, such as appliances, buildings, cars, and infrastructure and are commonly discarded after use. This "linear model" from extraction to manufacturing, use and disposal has led to resource depletion, production of waste and extensive use of energy [2]. As a result, greenhouse gas (GHG) emissions associated with the production of structural materials have increased rapidly from 5 to 12.1 $GtCO_2eq$ over 1990–2019, while their share in global GHG emissions has also grown from 15% in 1990 to 23% in 2019 [3]. This poses increasing challenges for meeting the Paris climate goals of limiting global warming to well-below 2 ℃ by the end oof the century [4], while the increase in the deployment of renewable energy reduces emissions from manufacturing sectors, but at moderate levels [46].

In this context, the 'circular economy' is introduced as an alternative to the current linear model [5]. Despite the various definitions found in the literature [5], the transition to circular economy aims to reduce primary material consumption, keep products and materials longer in use, recover or recycle materials and reduce losses [6]. By reducing primary material consumption, the circular economy will reduce the depletion of resources and environmental degradation risks, while also cutting the energy consumption and GHG emissions related with all stages of materials' production. Therefore, there are strong synergies between the circular economy and climate change mitigation towards achieving net zero emissions by mid-century, which are highlighted in recent literature including the International Resource Panel [1]. The role of circular economy (CE) towards the transition to climate neutrality has been acknowledged by the European Commission, as an integral part of the EU Green Deal, the Circular Economy Action Plan [7] and the "Clean Planet for all" long-term mitigation strategy [8], while CE is also discussed in the 14th 5-year China's plan.

Circular economy presents a great potential for emissions reduction, while creating new opportunities for the industry. The study of Material Economics [9] has shown that ambitious demand side measures in the form of materials recirculation, increased product efficiency and circular business models can reduce emissions from the heavy industry[1] by up to 60% in 2050 compared to 1990. Circular economy offers large opportunities for a more efficient use of materials, complementing the efforts in increasing energy efficiency, but requires large socio-economic structural changes and industrial re-organisation. It is therefore important that circular economy considerations are integrated in national low-emission development plans and should be jointly assessed with low-emission strategies, as [47] showed that there is a lack of literature scientifically scrutinizing the relationships between a hydrogen economy and the United Nations Sustainable Development Goals (SDGs). The transition towards a circular economy has several social, political, and sustainability aspects that should be investigated. The study [48] provides useful insights into how green recovery stimulus, driven by circular economy (CE)-based solid waste management (SWM)

[1] Heavy industry refers to an industry that produces large industrial products, which requires large and heavy machinery and facilities and involves complex and energy-intensive production processes. Heavy industry is dominated by large companies, as it is very capital intensive and requires significant investment in heavy equipment, massive buildings, large machine tools, and extensive infrastructure.

could assist in attaining the UN-SDGs and how green jobs can be created by investing in recycling infrastructure. The literature argues that CE-based product designs and business models would emphasize multifunctional goods, extending the lifespan of products and their parts, and intelligent manufacturing to help the public and private sectors maximise product utility (reduce waste generation) while providing long-term economic and environmental benefits. However, practical demonstrations of CE impacts in real-world contexts are currently limited, but one of them [49] showed that service-oriented, event-driven processing and information models can support the integration of smart and digital solutions in current CE practices at the factory level. The links of CE strategies with social and sustainable development and further analysed in [50].

Despite its potentially large contribution to achieving the climate targets, there is relatively limited analysis on the potential role of circular economy (CE) in the context of the energy transition. Circular economy is not adequately (and in most cases not at all) represented in most energy-economy and Integrated Assessment Models (IAMs) which are often used for climate policy analysis [10]. Most studies analysing the challenges and opportunities of circular economy use bottom-up methodologies focusing on the technical processes related to the CE and are often based on case studies, without considering the fully-scale CE implications on the entire energy system and associated emissions. This is an important research gap, which makes it difficult to analyse the interplay between climate policies and CE strategies. The paper aims to expand the current literature by consistently integrating circular economy in a state-of-the-art global energy system model with a focus on the most energy-intensive industrial activities. The novelty of the study is related to the consistent integration of CE strategies into a comprehensive energy system model that enables the assessment of their systemic implications on energy and economy systems. Through detailed scenario analysis, the potential synergies and trade-offs between ambitious climate action and resource efficiency are analysed, examining the role that CE strategies may play on the road to achieving the Paris goals. The study provides a detailed assessment of the systemic effects of circular economy on the future evolution of emissions, energy system transformation in major sectors, and related investment needs and improves the understanding of the interlinkages between climate mitigation, energy efficiency and circular economy measures.

The rest of the paper is structured as follows: Section 2 reviews the interplay between circular economy and the transition to a low-carbon economy and introduces the methodology used in the study. Section 3 presents in detail the model-based scenario results, focusing on the role of circular economy towards meeting ambitious climate targets. Section 4 discusses the key findings of the analysis and concludes.

2. Materials and methods

2.1. Review of circular economy in the transition to a low-carbon economy

Energy-intensive industries including iron and steel, chemicals, cement etc are commonly considered difficult to decarbonise due to the limited technological options available, their links with energy supply (to provide green electricity and hydrogen) and the high costs associated with shifting to low-carbon alternatives [4]. Reducing material consumption and production via CE strategies can complement other climate policies related to decarbonisation and energy efficiency [11]. The heavy industries can reduce their emissions and environmental footprint by decreasing the required amount of energy and raw materials through increased energy efficiency and the implementation of CE strategies, requiring the conversion of most material fluxes into closed loops. Due to the required speed of emission reductions and challenges in difficult-to-decarbonise energy-intensive sectors, CE strategies might play an important role in meeting ambitious climate targets [1,12]. A circular economy would increase the availability of raw materials for the sectors that manufacture low-carbon technologies, such as cobalt and li-ion for batteries or rare earths for wind turbines. The huge volume of toxic electronic waste (e.g., from smart phones) could provide feedstock for materials with the potential to increase electrification of the energy system, including the electronic components of batteries and photovoltaics. In addition, industrial symbiosis can offer a decarbonisation opportunity for some industrial sectors by re-using waste from other sectors as raw material input.

The current economic model in most countries is close to linear, often described by extraction, production, use and disposal of materials. In a circular economy, raw materials are sourced sustainably and used more efficiently in the entire chain of activities from product design, manufacturing, use, repair, disassembly, remanufacturing and reuse of products. The product components are gradually recycled after degradation minimising waste, with each component allowing for a different number of reuse cycles (Figure 1). The current model could lead to a moderate circular economy, with increased recycling and some limited reuse. However, the transition to a circular paradigm requires the transformation of the current value chain in the economy; the purchase and consumption of products will decline, their durability will increase and sharing practices need to emerge [8]. The manufacturing processes should be redesigned so that material losses are minimised in all lifecycle phases of materials and products, potentially leading to a diversified reuse across the value chain; for example, cotton clothing first reused as second hand apparel, then as fibre-fill in wood industry and in stone wool insulation for construction.

In a circular economy, companies may sell less products than in the current linear paradigm and may experience reduced revenues, but new value creation opportunities will arise aiming to retain values in the economic system. First, energy and material costs per product are expected to decline due to lower needs for primary resources, while new services—enabled by the digitalisation of the economy—will support reusing or sharing the use of products and offer lifetime prolongation for products. This will maximise the utility of the customers, while significantly reducing environmental impacts, the use of raw materials, energy resources and associated GHG emissions. The quantities of virgin materials used as feedstock in manufacturing processes will reduce, as they will be increasingly replaced by recycled and uncontaminated materials, which require much less energy intensive processes, and by the cascading use of materials and reduced material loss during the processing phase. However, some materials, like plastics, are more difficult (due to their chemical features and/or economic costs) to recycle than others, such as metals, glass, and paper [1,2]. Materials like metals and glass can either be recycled infinitely with proper recycling and circular strategies, while paper can be recycled 5 or more times before material integrity is compromised [8]. This means that while recycling of metals, glass, and paper brings energy savings, with the current infrastructure it is not chemically possible or economically viable to reintegrate a large portion of plastics with current technology [8]. Most plastics cannot be recycled at all, only downcycled to a different plastic of inferior mechanical quality, to which virgin plastic is added to maintain performance. As such, recycling will have much greater impact in achieving a transition to a CE in some sectors and products than in others.

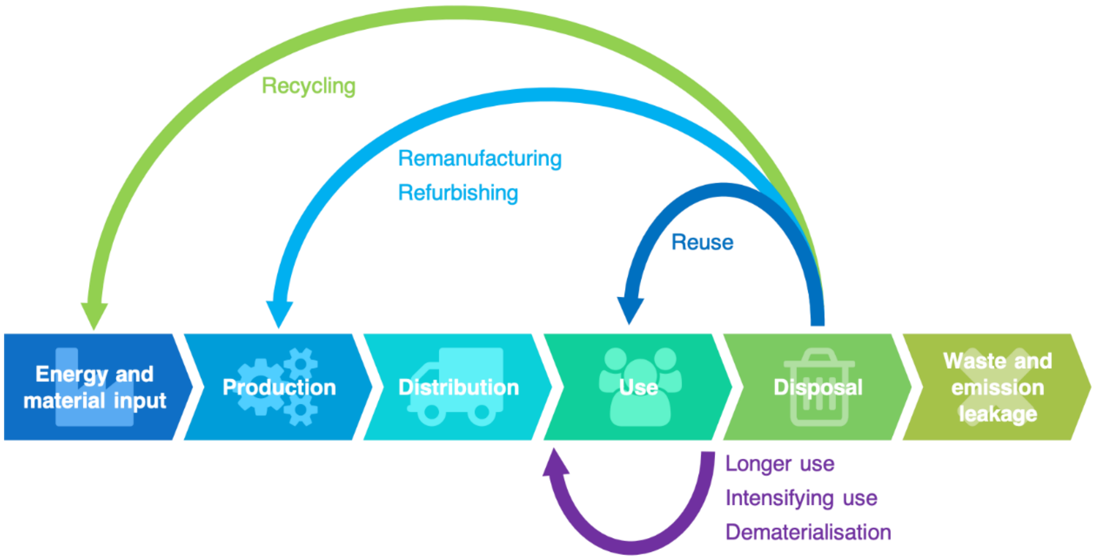

Figure 1. A circular economy. Figure adapted from [13].

The transformation towards a circular economy paradigm requires changes to product design and business models of involved industries. Manufacturing firms would be required to develop genuinely new products, with similar functionality for end users but lower energy and material use and associated emissions. The circular economy paradigm may also be complemented by the emergence of mobility-as-a-service with cars increasingly shared and operated in fleets; this will increase the car occupancy rate but will reduce the total car fleet and the materials required for their production.

Resource efficiency in industry is key for the circular economy, as it results in reduced needs for raw materials, increased recycling, and minimisation of waste and material loss across all lifecycle phases of each product. Circularity of metals and recycling of raw materials from low carbon technologies is an integral part of the low carbon transition. The EU is at the forefront of the circular economy and has increased the use of secondary raw materials with recycling rates of metals such as iron, aluminium, zinc, chromium, or platinum already reaching 50% [1]. However, additional effort is required to increase the secondary production of rare earths and gallium, which are needed in high-tech applications and renewable energy technologies and storage batteries [14]. Despite the potential recyclability of raw materials, a large part of future material demand will be provided by primary raw materials. In addition, recycling opportunities will fully materialise with a lag of several years or several decades (in the case of buildings) due to the long-time spans until the various products (e.g., cars, infrastructure, equipment, appliances) reach the end of their lifetime.

Materials and products consumed today are largely produced from raw materials (e.g., metal ores, hydrocarbons, biomass) and disposed of after use, creating waste. However, CE strategies including re-use, remanufacturing, and recycling, can reduce the reliance to primary resources and transform the supply chain in more, or even entirely, circular ways [15]. According to the International Resources Panel [16] resource efficiency policies could reduce global extractions by 28% by 2050. Combined with ambitious climate action, such policies can reduce global GHG emissions by about 62%. A recent study [9], focused on energy-intensive sectors like steel, plastics, aluminium, or cement, estimates that the transition to CE could reduce EU emissions by 300 $MtCO_2$ and global emissions by 3.6 $GtCO_2$ annually until 2050. In addition, the full recycling of plastic waste would save the equivalent to 3.5 billion of oil barrels per year. However, the study shows that the future demand of such materials will lead to emissions exceeding the carbon budget compatible with Paris mitigation goals, even if implementing energy efficiency and low-carbon measures.

The potential contribution of the CE towards the EU transition to a low-carbon economy is widely recognised [1,7,9]. In 2015, the European Commission published its Action Plan for the Circular Economy [7], which aims to stimulate EU's transition towards a circular economy, boost competitiveness, foster sustainable growth and generate new jobs. It covers the whole chain of activities from production to consumption, waste management and the market for secondary raw materials. In 2018, the Commission launched the EU Strategy for Plastics in a Circular Economy [17], targeting the production and incineration of plastics. As part of its effort to transform Europe's economy into a more sustainable one and to implement the Circular Economy Action Plan, in January 2018 the Commission adopted a set of measures (COM (2018) 29 final), including: a Europe-wide EU Strategy for Plastics in the Circular Economy, a Communication on options to address the interface between chemical, product and waste legislation that assesses how the rules on waste, products and chemicals relate to each other, a Monitoring Framework on progress towards a circular economy at EU and national level. It includes ten key indicators which cover each phase—i.e., production, consumption, waste management and secondary raw materials—as well as economic aspects—investments and jobs—and innovation. The Report on Critical Raw Materials and the circular economy highlights the potential to make the use of the 27 critical materials in our economy more circular.

The partnership of industries, sharing their infrastructures and their material inputs and outputs (including waste), is another way to optimise resource use and reduce emissions, enabled by digitalisation[2]. Exploiting the strong interlinkages among industries, the intensified exchanges of materials, energy and services, can enhance environmental sustainability and achieve mutual economic benefits [18]. This option is mostly applicable to specific industrial subsectors and selected industrial sites in Europe, which fulfil the requirements for infrastructure and access to specific resources. It is more efficient for industries closely located to each other, facilitating the exchange of materials and resources; for example, SPIRE project[3] systematically mapped and assessed the geographic dimension of industrial symbiosis for cement, steel, refining and chemical industries, identifying five potential symbiosis sites/hotspots in Europe.

2.2. The PROMETHEUS model

PROMETHEUS is a comprehensive energy system model focusing on technology uptake analysis, energy price projections, and assessment of climate policies [19,20]. It captures the

[2] The carbon footprint of digitalization would increase driven by increasing requirements for servers and data centers that need to run constantly. But, in the decarbonization context, electricity would be carbon-free before 2050, indicating relatively limited emissions due to digitalization. A recent study has estimated that digitalization is responsible for about 3.5% of global emissions, but data centers account for only 15% of this impact, i.e. about 0.5% of total emissions [52].

[3] https://www.spire2030.eu/epos

interactions between energy demand and supply at regional and global level and provides detailed projections of energy consumption by sector, fuel mix, electricity production mix by technology, carbon emissions, energy prices and investment to the future. PROMETHEUS can provide medium- and long-term energy system projections up to 2050, exploring the impacts of alternative energy and climate policy measures (e.g., carbon pricing, subsidies for renewable energy, energy efficiency standards, fossil fuel taxation, promotion of clean fuels etc).

In PROMETHEUS, market equilibrium is ensured with each representative agent (e.g., energy producer or consumer) using information on prices to make decisions about the allocation of resources. The interactions of agents are governed by market dynamics with market-derived prices to balance energy demand and supply in each sector (e.g., electricity production). The national fuel markets are also integrated to form an international (global or regional) market equilibrium for crude oil, natural gas, and coal. The model produces projections of global and regional fossil fuel prices, which depend on demand, supply, technology, and resources (Figure 2). Thus, PROMETHEUS covers in detail the complex interactions between energy demand, supply, and energy prices at the regional and global level. Its main objectives are: (1) to assess climate change mitigation pathways and low-emission development at national or global levels; (2) to analyse the energy system, economic and emission implications of a wide spectrum of energy and climate policy measures, and (3) to explore the economics of fossil fuel production and quantify the impacts of climate policies on the evolution of global energy prices [21].

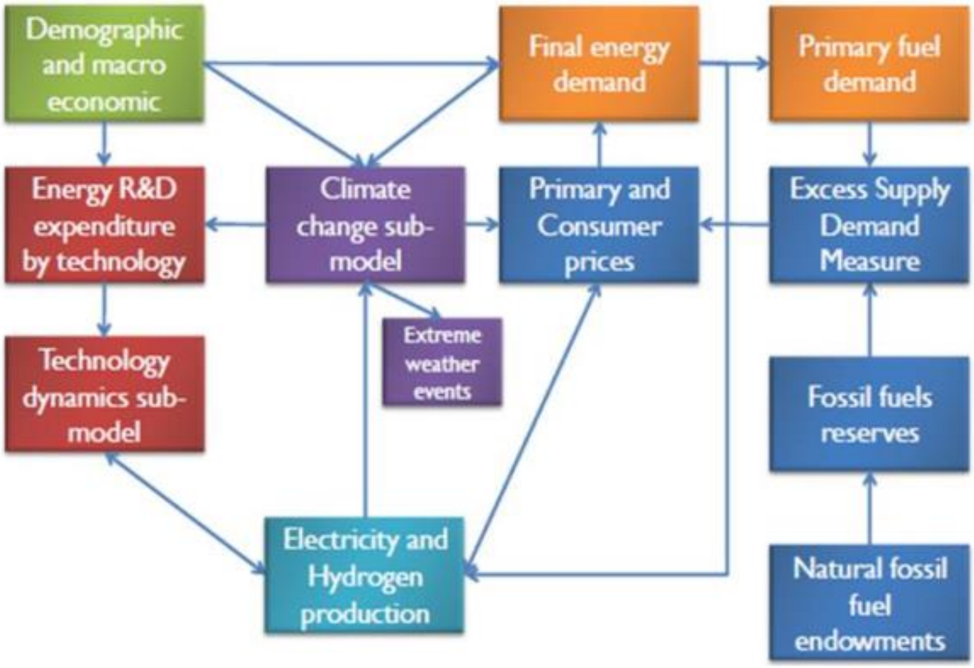

Figure 2. PROMETHEUS Flow Chart.

PROMETHEUS quantifies CO_2 emissions and incorporates environmentally oriented emission abatement technologies (such as various renewable energy sources, electric vehicles, heat pumps, biofuels, energy efficiency, Carbon Capture and Storage, Carbon Dioxide Removal options) and policy instruments, such as carbon pricing schemes that may differentiate by region and economic activity. The model includes a complete accounting of energy demand and supply by sector and energy product and endogenous representation of energy prices. PROMETHEUS represents: the EU, China, India, the USA, Western Pacific region (Japan, S. Korea, Australia, New Zealand), Russia and CIS economies, MENA region (Middle East and North Africa), Emerging economies and Rest of world [22]. In PROMETHEUS, the regional developments of energy demand and supply, the inter-fuel substitutions, energy and climate policies and hydrocarbon resource assumptions influence the evolution of the global energy system and international fossil fuel prices. The modelling framework can be used for the impact assessment of energy and environment policies, including carbon or energy taxation, subsidies, clean energy, and energy efficiency promoting policies, and technology standards [22,23].

A detailed representation of the major energy- and carbon-intensive industrial sectors is included in PROMETHEUS, which represents the Iron and Steel sector, building materials (including cement), production of chemicals, non-ferrous metals and paper and pulp industries. In each industrial sector the model represents several types of industrial processes, technologies and energy forms and models the link between technology and processing types based on substitution possibilities (e.g., steel produced from integrated steelworks vs steel produced from electric arcs) as well as complementarities. The substitution possibilities combined with the structure of industrial processes represented in PROMETHEUS is a solid basis to estimate the realistic possibilities of the transformation in the industry sector, induced e.g., by the direct electrification and the uptake of low-emission fuels. Recent modelling improvements enable the explicit representation of primary versus secondary production of energy-intensive materials, including steel, paper, aluminium, glass, and clinker. These projections depend mostly on activity assumptions and policy drivers, regarding recycling and circular economy, which may differentiate by scenario. The modelling framework is therefore designed and well-equipped to address the questions about the medium- and long-term effects of circular economy and its contribution to meeting ambitious global climate targets. The specific operationalisation of energy efficiency and circular economy in applied models in discussed in section 2.3.

2.3. Operationalisation of energy and resource efficiency in models

Energy efficiency strategies are key pillars towards achieving deep emissions reduction, but they are often neglected or poorly represented in energy-economy models, which tend to focus more on supply-side mitigation options [24]. However, recently the most advanced energy system models have improved the representation of efficiency measures and demand-side mitigation options, given the increasing importance of energy efficiency for climate strategies [19,25]. In this context, PROMETHEUS includes a detailed and self-consistent representation of energy efficiency policies and related instruments, including efficiency standards, energy labelling, regulation, promotion of more efficient energy forms and technologies, strategies for renovation of buildings etc. These measures are inserted in the model either in the form of price incentives (e.g., cost subsidies, changes in energy and carbon taxation) or in the form of constraints, i.e., on the rate of buildings' renovation or the phase-out of energy and carbon-intensive technologies (e.g., oil boilers or diesel cars). These efficiency measures often apply to the buildings and transport sector influencing consumer decisions related to the investment and/or operation of energy equipment, appliance, and passenger cars.

In the industrial sector, on top of energy efficiency measures, resource and material efficiency strategies and circularity play a prominent role driving energy and emission savings [5,26]. Thus, modelling should capture the potentials and costs of product recycling and re-use, improved waste management, substitution towards more efficient materials, reduced need for virgin materials, and the shift of manufacturing processes to secondary, recycled materials that have lower energy and carbon requirements (e.g., scrap steel, recycled paper, plastics etc). This means that primary industrial output (in volumes) of specific sectors would decline [8], while the impacts on respective value added depend also on the emergence of recycling and circular services. Overall, the literature on circular economy is growing, but so far it does not provide analytical information [9]. The EU's long-term strategy [8] and relevant literature ([9,13,27]) include a detailed review on the circular economy impacts on industrial production by sector, which are also utilised in the current study. Table 1 presents the assumed effects of resource efficiency and circular economy on primary industrial production based on a realistic implementation of circularity in energy intensive sectors, without assuming overly ambitious transformation and disruptive options (e.g., 3D printing). It should be noted that the assumed levels of output reduction can be considered conservative compared to the circular economy literature, which is presented below. If buildings, infrastructure, and cars are produced and used more efficiently, this would trigger additional reductions in material requirements.

Table 1. Impact of Circular Economy on primary energy-intensive production in 2050.

	% Reduction of primary material volumes from Baseline	Most important Circular economy strategies by sector
Iron & Steel	6%	Higher steel recycling; Increased use of scrap steel; reduced demand for steel (e.g., from cars, constructions etc)
Chemicals & Plastics	9%	Improved recycling rates of plastics; Product standardisation, improved collection, and sorting; Cascading use of plastics with down- and up-grading; Wood fibre products replacing plastics
Paper & Pulp	12%	Maximise recycling and re-use of paper; Improve material efficiency; Improve the collection, sorting and Ecodesign for recycling; New technologies like steam forming without wetting and drying;
Non-metallic minerals (including cement)	8%	Recover up to 30–40% of unused clinker from concrete at end to life; lower cement demand (e.g., re-use of building components, wood-based construction);

The Iron and Steel sector accounts for about 8% of global emissions in 2019, so it is a key sector for emission reduction efforts. There are different routes by which steel is produced. Crude or primary steel is produced from iron ore and secondary steel is produced from recycled steel, but this is constrained by limited scrap availability and thus scrap accounts for about 35% of global steel production [28]. These two routes use different technologies and different energy sources [28], but secondary steel production is about 70% less energy intensive than making steel from iron ore (primary production) [29]. The share of scrap in primary steel production varies among countries and years. In the context of circular economy, the shift from primary steelmaking to secondary smelting of steel scrap depends on various factors, including the availability and quality of scrap metal in international markets and the quality of the final product. Currently, many factors reduce the steel amounts that can be recycled including low collection rates, downgrading of steel, lack of incentives to recycle steel, losses in recycling processes and copper contamination. These can be resolved by improving circular economy practices, increasing the availability of scrap steel from the current share of 35%–40% up to 80% according to [9] and significantly reducing energy requirements and CO_2 emissions. In the circular economy context, demand measures (e.g., reduced number of cars) could further reduce primary steel production to the point where the available scrap steel would be able to cover most of the steel demand [9].

Significant potential lies also in the increased material efficiency and substitution, especially related to carbon-intensive materials like cement. Although cement cannot be recycled as other materials, there is an opportunity to recover up to 30–40% of unused clinker from concrete at end to life, replacing up to 60% of new cement production and saving almost half of associated emissions [30]. In addition, cement requirements could be reduced if buildings are designed for disassembly and building components can be re-used, while wood-based construction can also reduce energy requirements and carbon emissions (despite its risks due to reduced stability and shorter lifecycle).

In the chemicals and plastics sector, the improved recycling of plastics can play an important role in the transition towards circular economy. Plastic waste can be significantly reduced by increasing the mechanical and feedstock[4] recycling up to 60–70% of yearly plastic waste volumes [26]. Another study finds that up to 60% of the global production of chemicals can be recycled and re-used [31], but this requires product standardisation, improved collection, and sorting. Increased circularity would result in both reduced use of raw material (of fossil origin), as well as less energy since recycled plastic is a less energy demanding process. However, with the current infrastructure it is not chemically possible or economically viable to reintegrate a large portion of plastics with current technology. In circular economy context, a cascading use of plastics would be introduced with downgrading or upgrading (with mechanical and feedstock recycling respectively) or after the plastics have degraded to energy recovery [8].

Paper and pulp sector also have a great potential for increased resource efficiency based on maximum recycling and re-use of paper, improved material efficiency and wood fibre products replacing plastics. Recycled fibre quality can be enhanced by improving the collection, sorting and Ecodesign for recycling. New recycling technologies like steam forming without wetting and drying could even further decrease energy demand in the paper industry [32]. Digitalisation might also provide the next generation of efficient recycling technologies [8].

Transport benefits from integrating the sharing economy and connected, cooperative and automated mobility, and making full use of digitalisation, automation and mobility as a service. The vehicle fleet is smaller relative to the Baseline, but it is utilised more, has higher occupancy rates,

[4] Mechanical recycling refers to the mechanical processing of waste plastics to produced recycled polymers. Feedstock recycling refers to the chemical or thermal processes breaking down polymers into products that can directly replace raw materials.

and it is renewed faster. The reduced vehicle fleet results in lower requirements for materials used in the automotive industry. Improved logistics and shifts from long-distance freight to near-sourcing, together with shifts towards rail and waterborne transport lead to further energy and emission savings. In the energy system, circular economy implies increased waste heat recovery, and conversion of waste material into useable heat, electricity, or fuel. Improved management and collection of organic waste and biomass cascading, increases the sustainable biomass use either as a feedstock or for biogas production in local bio-refineries.

2.4. Scenario design

The paper aims at exploring the effects of a strong push in circular economy and energy efficiency across the global energy system, with a focus on energy-intensive industries, under stringent decarbonisation policies. For this purpose, we design five scenarios (Table 2) based on specific assumptions with regard to (i) climate change mitigation targets, (ii) energy efficiency improvements, and (iii) circular economy considerations. These scenarios are then implemented in the PROMETHEUS model.

Table 2. Summary of key assumptions used in the series of scenarios.

Scenario name	Scenario Description	Key assumptions
REF	Continuation of existing energy and climate policies, no strengthening of policies after 2030	Energy system follows current trends, energy efficiency improves at historical levels
2 DEG	Global 2016–2050 carbon budget of 850 Gt CO_2 (compatible with well-below 2 ℃)	Cost-optimal transition to 2 ℃, based on universal application of carbon pricing
2 DEG_CI	Same carbon budget as 2DEG. Increased energy and resource efficiency, including circular economy	The transition to 2 ℃ based on accelerated energy efficiency and circular economy
1.5 DEG	Global 2016–2050 carbon budget of 600 Gt CO_2 (compatible with a 1.5 ℃)	Cost-optimal transition to 1.5 ℃, based on universal application of carbon pricing

The REF scenario is based on the continuation of already legislated energy and climate policies, in consistency with [33]. The global energy system develops in line with current trends including existing climate policies until 2030 and further cost improvements in low-carbon technologies; beyond 2030, no binding emissions reduction targets are imposed. The energy intensity of GDP is assumed to keep improving at rates close to historical rates in each region. The REF scenario serves as a benchmark to compare the results of other scenarios, which explore possible realizations of a low-carbon energy system driven by decarbonization policies and energy efficiency targets [34], including circular economy considerations.

The 2 DEG scenario achieves a cost-optimal emissions reduction trajectory compatible with a well-below 2 ℃ increase in global temperature, in line with the Paris Agreement goal. Global CO_2 emissions from fossil fuels and industrial processes over 2016–2050 are constrained to a budget of 850 Gt CO_2 in line with [35]. A global carbon pricing scheme applies uniformly across all regions and sectors. The carbon price emerges endogenously in PROMETHEUS as the dual variable related to the maximum allowed carbon emissions by 2050. Energy system decarbonization is induced by high carbon pricing that incentivizes the uptake of renewable energy, electrification, clean fuels, and energy efficiency improvements.

The 2 DEG_CI scenario achieves the same carbon budget constraint as the 2 DEG, but higher energy and resource efficiency improvements are realized in all demand sectors by 2050. This is induced by the imposition of energy efficiency policies (e.g., subsidies for the renovation of buildings or the purchase of electric cars), the uptake of more efficient technologies (e.g., heat pumps), which are usually accompanied by higher capital costs [25], and transition to circular economy paradigm with increased recycling rates of materials and accelerated resource efficiency. The scenario aims at showing the effects of demand-side changes on the road to decarbonization, including consumers' shift towards purchasing efficient technologies and energy forms and industries' shift to circular economy. These changes can be induced by policy measures targeting the stringent implementation of energy labeling, efficiency standards, and building codes, the gradual phase-out of inefficient energy appliances and equipment, increased renovation rates, and a move towards circular economy. These may include measures to enhance resource efficiency, increase recycling rates of materials and products, standardise recyclable material and improve systems for waste management [31]. In this way, the demand for primary resources and materials is lower relative to 2 DEG as shown in Table 1, due to the increased reuse and recycling of products and materials, reduced waste, and the replacement away from resource-intensive products. These are accompanied by changes in consumer lifestyles with adoption of environmentally friendly practices, including e.g., more rational use of energy in the built environment, shifts towards less carbon-intensive transport modes, emergence of Mobility-As-A-Service, sharing mobility and active mobility forms [8]. In the industry sector, the scenario includes several circular economy measures, e.g., increased use of scrap steel, ambitious recycling of plastics and paper, substitution of plastics by bio products, improved material efficiency, material substitution by biomass, concrete recycling and re-use, which are combined with increased use of biomass, renewable energy, and RES-waste.

The last scenario of the study (1.5 DEG) has the same logic as 2 DEG but aims to achieve a more ambitious climate target. In particular, global cumulative carbon emissions in 1.5 DEG are constrained to 600 Gt CO_2 over the 2016–2050 period, resulting in a global temperature increase of 1.5 ℃ by the end of the century [36]. This scenario explores the impacts of ambitious and coordinated climate action by all countries to limit global warming to below 1.5 ℃ (as introduced in the Paris Agreement) by implementing universal carbon pricing across all regions and sectors.

Assumptions for future development of the main socio-economic drivers—population and GDP growth—in PROMETHEUS are based on the second Shared Socioeconomic Pathway (SSP2) developed in [37]. However, in this paper the SSP2 trajectory is modified to reflect the impacts from COVID-19 and the expected developments in the post-COVID era. These modifications entail short-term GDP projections from official sources, including OECD Economic Outlook (November 2020) [38], and World Bank Global Economic Prospects (June 2021) [39]. PROMETHEUS is calibrated to reproduce the impacts of COVID-19 on economic activity in 2020: a 4.5% lower global GDP relative to 2019 levels. After 2021, assuming a strong and effective vaccination programme and no further major outbreaks, GDP projections follow a V-shape growth recovery or an L-shaped recovery in level terms [40].

3. Results

3.1. Impacts on emissions and carbon pricing

The policy scenarios examined influence the development of energy-related CO_2 emissions, as shown in Figure 3. The REF scenario shows a modest increase in global emissions over 2020–2050, despite the robust growth of global GDP [33], indicating a relative decoupling of emissions and energy use from GDP growth, in line with recent multi-model comparison exercises [4,40,45] and the IPCC Special Report on 1.5 ℃ [36]. This is induced by the expansion of low-carbon and energy-efficient technologies in energy supply and demand induced by technology cost reductions (e.g., PV, wind turbines, batteries, electric vehicles) and the continuation of already legislated climate policies. The latter are realized in PROMETHEUS through constraints in model equations which influence the development of the energy mix and the uptake of fossil-fuel or low-carbon technologies in each sector. The impacts of the European Emission Trading System (ETS) are also simulated, resulting in the small increase in global average carbon price in the REF scenario (Table 3).

Global carbon prices increase with the level of emissions mitigation effort. In 2 DEG scenario, the global carbon price increases to 81 $ 2015/tn CO_2 in 2030 and further to about $ 290 in 2050 as the ambition of climate action increases and further uptake of available mitigation options faces constraints. The scenario with high energy efficiency and circularity requires lower carbon prices to achieve the same climate target, as shown in Table 3 where the carbon price in 2 DEG_CI is 35% lower than in 2 DEG in 2050. The implementation of ambitious energy efficiency policies, standards and regulation combined with the transition to a circular economy may reduce the need for high carbon pricing to achieve the same mitigation target. In turn, this is expected to positively influence the social and political acceptance of climate policies, as carbon and energy taxation has regressive distributional impacts, posing a high cost burden to low-income households [41], and often raises social concerns as manifested in the Yellow Vests movement [42]. The exhaustion of available emission reduction options and the uptake of more expensive technologies to meet the 600 Gt carbon budget in the 1.5 DEG scenario requires even higher carbon prices, which increase to about 450$/tn CO_2 in 2050, indicating the difficulties to reach close to net zero emission levels.

Table 3. Global carbon price in alternative scenarios by 2050 ($ 2015/tn CO_2).

	2030	2040	2050
REF [5]	10	12	16
2 DEG	81	153	291
2 DEG_CI	68	128	188
1.5 DEG	175	267	457

The implementation of high carbon pricing results in large emissions reductions, as mid-century global CO_2 levels in 2 DEG scenarios are 80–85% lower than in REF. The emission cap imposed triggers an increase in carbon price which applies to all regions and sectors to ensure that the global climate target is achieved with the lowest possible cost through the equalization of marginal abatement costs globally. The 2 DEG and 2 DEG_CI scenarios achieve the same carbon budget by

[5] This refers to the average carbon price across regions (as there is no global carbon price in REF)

definition, but emissions are reduced faster in 2 DEG_CI over 2025–2035 triggered by the increased energy and resource efficiency and circularity. This is reversed after 2040 as 2 DEG requires higher carbon prices and thus incentivizes larger changes in energy supply in the longer term. This scenario shows that utilizing energy efficiency and circular economy measures could prove an effective way to bridge the effort gap between 2 ℃ and 1.5 ℃ without requiring very high CO_2 prices. Moreover, the 1.5 DEG scenario imposes a more ambitious constraint on global carbon budget resulting in emissions reduction of more than 92% (hence close to net zero) in 2050 but requiring very high carbon prices—almost twice as high as in 2 DEG.

Figure 4 shows the global cumulative emissions over 2016–2050 for major emitting sectors by scenario. In REF, most emissions come from the energy supply sector which accounts for about 44% of total emissions, mostly due to coal and gas-fired power plants. Energy demand accounts for about 50% of global emissions, with transport accounting for 48% of those, as a result of rapid motorisation in developing regions due to rising incomes and the continuous dominance of oil products. The 2 DEG scenarios result in large emissions reductions in all demand and supply sectors. The cost-optimal 2 DEG scenario leads to a rapid decarbonisation of electricity generation, and thus the share of energy supply in global emissions declines, while the share of energy demand increases from 50% in REF to 59% in 2 DEG. High energy efficiency improvements and increased circularity in 2 DEG_CI lead to drastic emission reductions in the demand side, which are projected to decline by an additional 15% below 2 DEG levels; this is accompanied by increased supply-side emissions in the form of reduced Carbon Capture and Storage (CCS) due to lower carbon pricing. The industrial sector is heavily impacted, as the transition to circular economy combined with the uptake of low-carbon energy forms would drive a reduction in sectoral global cumulative emissions of 37% below REF levels and 17% below 2 DEG levels, indicating high emission abatement potential relative to previous studies [45,51] which did not explicitly account for circular economy strategies. The high carbon pricing imposed in the 1.5 DEG scenario would lead to further emission reductions in all energy demand and supply sectors and increased uptake of CCS to compensate for emissions in hard-to-abate sectors.

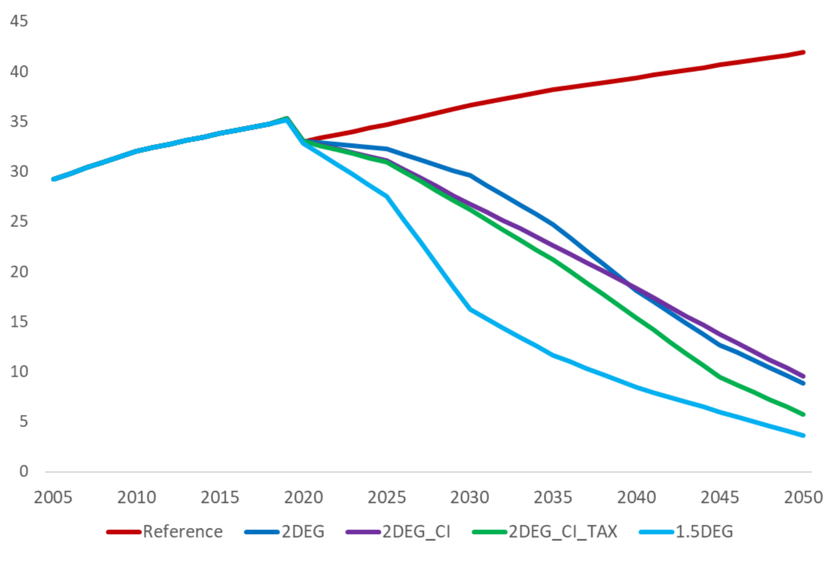

Figure 3. Evolution of global CO_2 emissions (in Gt CO_2).

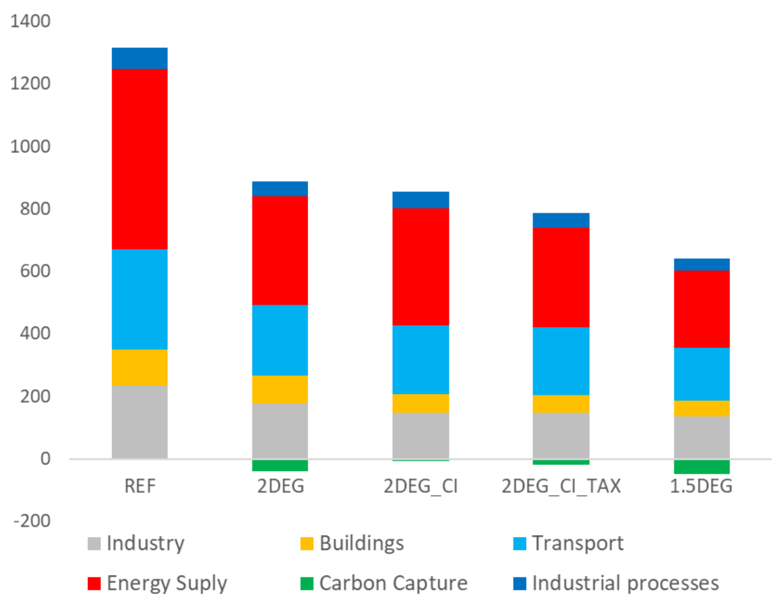

Figure 4. Global cumulative CO_2 emissions by sector over 2016–2050 (Gt CO_2).

3.2. Impacts on energy demand

The section analyzes projections of final energy consumption (FEC) across policy scenarios in industry, buildings (including the residential and commercial sectors) and transport. The REF scenario shows a constant increase in energy consumption driven by robust growth of economic activity, rising standards of living especially in developing countries, and the lack of ambitious climate policies. Global FEC is projected to grow by 1.2% annually in the 2020–2050 period, with developing economies representing most of this growth and developed economies facing saturation in their energy requirements. The imposition of strong carbon pricing would lead to reduced FEC globally, induced by the uptake of more efficient energy forms and technologies (e.g., electricity instead of oil products in passenger cars). The implementation of ambitious efficiency measures, standards and policies and the transition to circular economy would lead to further energy savings with energy consumption in 2 DEG_CI declining by 14% below 2 DEG and 33% below REF levels in 2050 (Figure 5). The final energy mix is also heavily impacted by strong climate policies with the consumption of coal and oil rapidly reducing in all demand sectors, while oil in 2050 is mostly used in specific transport segments (e.g., freight transport, aviation, navigation) and in petrochemicals production. The major trend in ambitious decarbonisation scenarios is the increasing electrification of energy end uses with electricity share in global FEC increasing from 20% in 2020 to about 43–46% in 2 DEG scenarios and more than 50% in 1.5 DEG scenario in 2050.

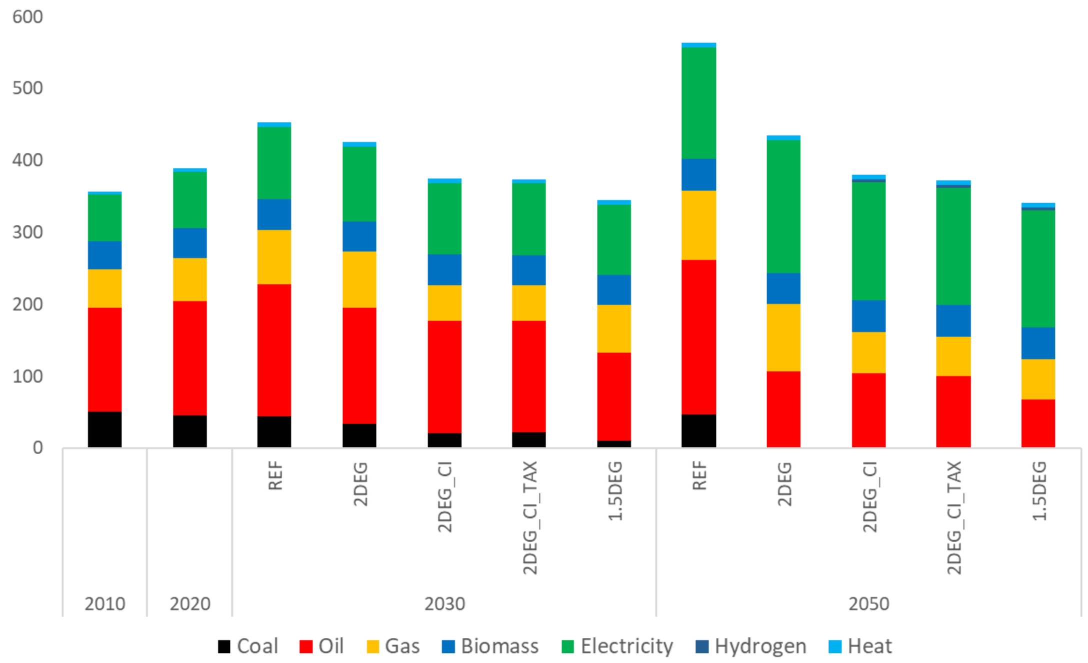

Figure 5. Evolution of global final energy consumption by fuel (in Mtoe).

Looking specifically in the industry sector, the REF projections show a steady increase in global energy consumption driven by increasing industrial manufacturing activity. In the absence of additional climate policies in REF, there are limited changes in the energy mix used with coal, gas, oil, and electricity being the main industrial fuels with a small contribution from biomass and heat. The imposition of ambitious climate mitigation policies causes a decrease in energy consumption, as more efficient technologies and energy forms increasingly replace the use of less efficient products. Ambitious energy efficiency policies and increased circularity of materials lead to further reductions of energy requirements in industry, with global FEC declining by 10% and 30% below 2 DEG and REF levels respectively in 2050, which is relatively higher compared to previous studies [45,51] which do not include circular economy considerations. This happens as the 2 DEG_CI scenario assumes reduced industrial output in certain industrial subsectors and increased secondary production of materials, which is less energy intensive than primary production (Table 1). The model-based analysis shows that fuel switching and accelerated energy and resource efficiency (e.g., increased circularity of cement, steel, paper, plastics, improved waste management etc) are the primary options towards industrial decarbonisation. In this context, all mitigation scenarios show that electrification of industries increases by 2050 but reaches a saturation level of around 50%–55% as some industrial activities and processes cannot be fully electrified, especially in energy-intensive high-temperature manufacturing [43]. To further reduce industrial emissions from hard-to-electrify processes, the use of hydrogen[6] emerges as a key transformation option for specific sectors (Figure 6),

[6] In the decarbonisation scenarios, hydrogen is mostly produced through electrolysis of renewable-based electricity (green hydrogen) with smaller amounts produced by Steam Methane Reforming with CCS, especially in regions with cheap gas resources like MENA and Russia.

including steel making [8]. In addition, PROMETHEUS shows that CCS technologies in biomass and fossil-fired industrial processes should be applied in low-emission scenarios.

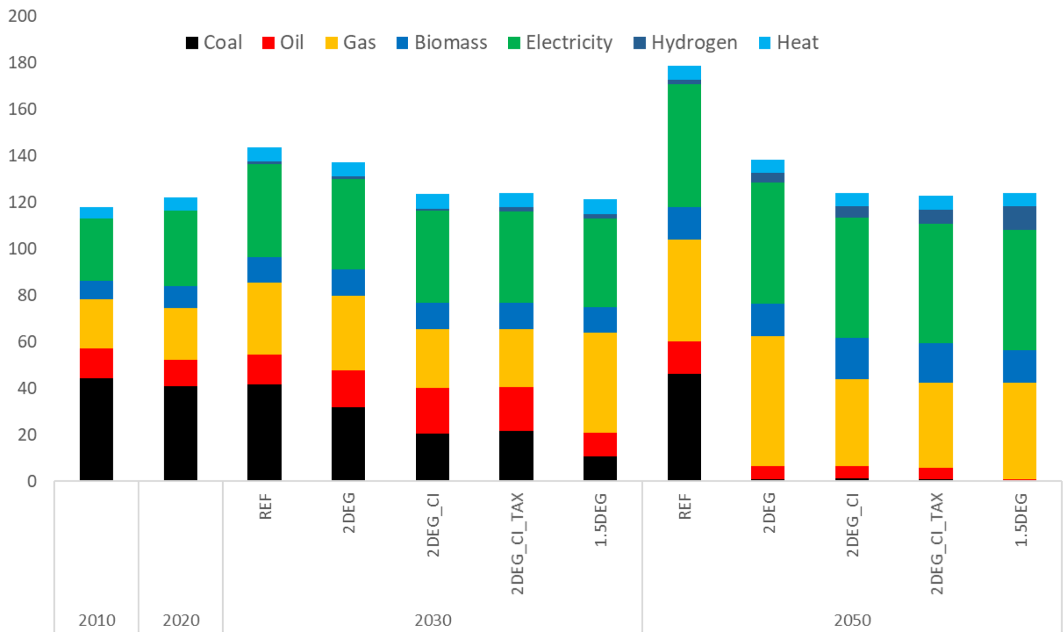

Figure 6. Evolution of global final energy consumption by fuel in industries (in Mtoe).

The buildings sector will also be transformed due to ambitious climate and energy efficiency policies (Figure 7). Energy consumption in REF is projected to increase with an annual rate of 1.1% per annum over 2020–2050, induced by growing global population and economic activity, increasing urbanization, and rising living standards that trigger increased purchase and use of heating and cooking equipment and electric appliances, mostly in developing economies. The imposition of ambitious energy efficiency measures and emission reduction constraints leads to a reduction of FEC in buildings, supported by the uptake of more efficient technologies, fuels and equipment, energy audits, LEED[7] certifications, energy efficiency building standards, the emergence of electricity for heating, the increased rate and depth of renovation and a more rational use of energy by consumers. Strong efficiency standards and policies cause a large reduction of energy requirements, with global FEC of buildings declining by 30% from REF levels (and 20% from 2 DEG) in 2050, compatible with [44] showing that under strong efficiency measures, energy consumption in buildings can decline by more than 40% compared to a current trends scenario. The use of oil in buildings is phased out by 2050 in mitigation scenarios, with only a small amount remaining in low-income African countries where the full switch to low-emission alternatives faces high challenges. The low-emission scenarios drive drastic changes in the global energy mix in buildings with a large-scale reduction of fossil fuels and traditional biomass, combined with increasing electrification of end-uses—with the share of electricity increasing from 35% in 2020 to 62–68% in 2050 in low-carbon scenarios in line with [45]—and uptake of green hydrogen and modern biofuels.

[7] Leadership in Energy and Environmental Design

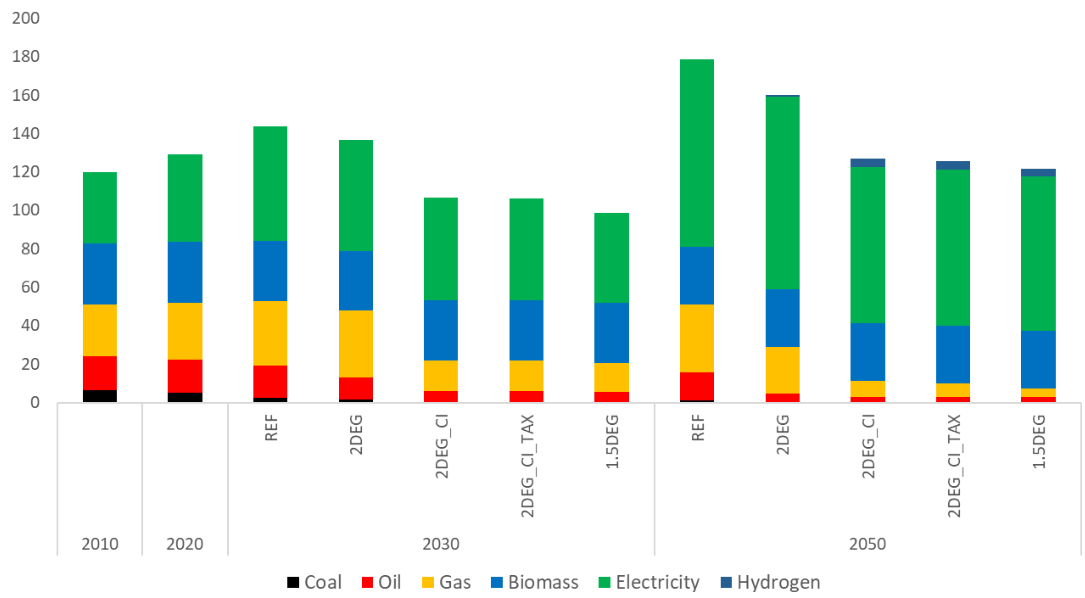

Figure 7. Evolution of global final energy consumption by fuel in buildings (in Mtoe).

Similar to the other demand sectors, global energy consumption for transport increases in REF by 1.4% p.a. over 2020–2050, driven by increasing population, activity and motorization in developing economies combined with lack of policies to facilitate the switch to low-emission fuels and less energy-intensive modes. In REF oil products remain the dominant transport fuel, as ICEs are widely used in transport modes, while biofuels and electricity gain a small share in transport energy mix by 2050. In mitigation scenarios, total energy consumption declines due to the switch to more efficient vehicles and energy forms (e.g., electricity instead of oil products) and the emergence of new business models (e.g., Mobility as a Service, shared cars) and less energy-intensive mobility practices (e.g., walking, using trains instead of aviation when available). High carbon pricing and energy efficiency measures radically change the transport fuel mix, as consumption in 2050 (that is close to current levels) is met by a combination of oil products, electricity, and biofuels at almost equal shares, while hydrogen also emerges mostly in freight transport. Energy consumption is further reduced in 1.5 DEG scenario, induced by the phase-out of conventional ICEs and hybrid fleets that are rapidly replaced by EVs in road passenger transport—supported by significant cost declines- and hydrogen fuel cells in freight transport [26]. Biofuels have a substantial contribution in the transport energy mix by 2050 (Figure 8), to decarbonize transport segments that are difficult or expensive to be electrified, including aviation and navigation. However, their increased uptake does not raise sustainability issues and does not put pressure on land resources and food prices, as total biomass demand remains below sustainability thresholds as specified in [36] and [37].

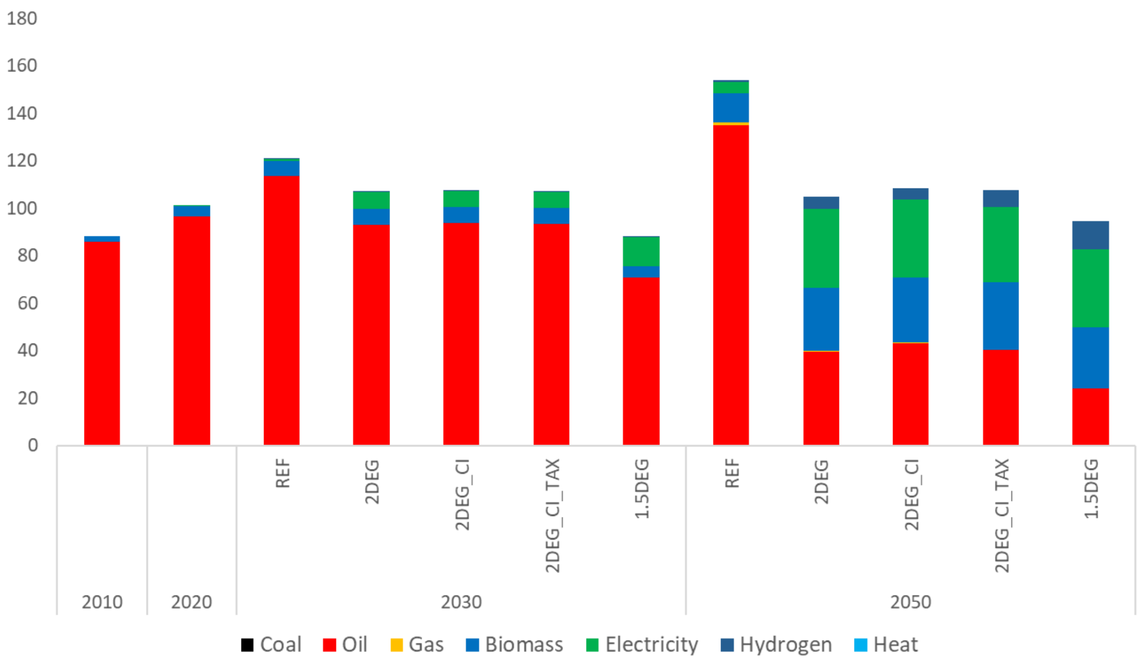

Figure 8. Evolution of global final energy consumption by fuel in transport (in Mtoe).

3.3. Impacts on energy supply and immature technologies

The imposition of strong emission reduction and energy efficiency policies would cause drastic changes in electricity production mix (Figure 9). In all scenarios, global electricity production is projected to increase by 2.1–2.5% p.a. over 2020–2050 because of increasing economic activity and population, rising standards of living and increasing electrification of energy end uses (section 3.2). The development of electricity requirements and the projected technology mix depend on various model assumptions for the evolution of energy consumption in each region, technology cost reductions, carbon price levels, technology potentials and changes in fuel mix and consumption patterns across demand sectors.

The REF scenario shows that global electricity requirements increase by 110% over 2015–2050. The changes in technology mix are driven by the increased uptake of renewable energy (especially PV and wind) triggered by their cost reductions. This leads to a growing share of renewable energy in global power mix, increasing from 23% in 2015 to 32% in 2030 and to 40% in 2050. Due to the lack of strong carbon pricing, coal-based generation maintains a share of 27% in 2050 (albeit reduced from 39.5% in 2015). Oil-fired production is phased-out before 2050, while the shares of nuclear and gas-fired generation remain close to their 2020 levels.

The implementation of strong climate policies drastically affects the levels and structure of the global power mix. Electrification of energy and transport services is a key mitigation option in all low-carbon scenarios, resulting in 13–19% higher global power generation in 2 DEG and 1.5 DEG scenarios with respect to REF in 2050, as global electricity use expands in transport, industries, and buildings to substitute for fossil fuels. Strong efficiency measures and increased circularity reduces electricity use in 2 DEG_CI scenario relative to 2 DEG, but power requirements are still higher than REF due to increasing electrification. High carbon pricing penalises the use of fossil fuels, with the share of unabated coal, oil, and gas in global power mix declining from 66% in 2015 to 39–43% in 2030 and further to 2–6% in 2050 across 2 DEG scenarios. The reduction is even faster in 1.5 DEG with fossil fuel share dropping to less than 10% in 2030 followed by a complete phase-out by 2040. In this context, renewable-electricity production scales up rapidly to compensate for declining fossil fuels with the share of renewable energy increasing from 23% in 2015 to about 47% in 2030 (67% in 1.5 DEG) and further to 70–77% in 2050, mostly driven by expansion of PV and wind (Figure 9). Nuclear power, hydrogen, and CCS (with fossil fuels and biomass) cover the remaining 23–29% of electricity supply, which is fully decarbonised by 2050. The uptake of CCS technologies depends on the specific scenario assumptions and is generally lower in scenarios assuming strong efficiency measures (2 DEG_CI) relative to 2 DEG and 1.5 DEG driven by carbon pricing. BECCS technologies are deployed in 2 DEG and 1.5 DEG, but this option is not required when ambitious efficiency measures and circularity are adopted in 2 DEG_CI, as emissions from the demand sector decline below 2 DEG without the need to invest in BECCS.

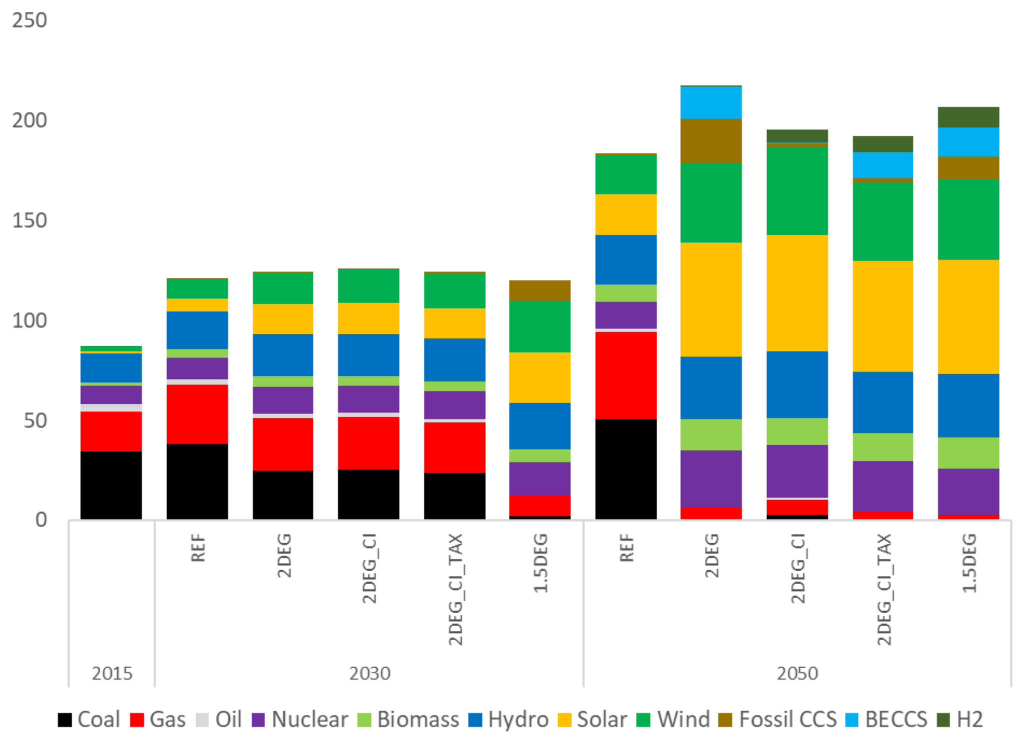

Figure 9. Global power generation by main technology in policy scenarios (in EJ).

In addition to reducing emissions from fossil fuel combustion, ambitious climate targets may require the uptake of technologies to remove CO_2 from the atmosphere [33,35]. The main mechanism for CO_2 removal considered in this study is the deployment of CCS in electricity production, industry, and fuel production. The uptake of CCS is triggered by high carbon pricing in low-emission scenarios, in quantities depending on scenario-specific assumptions. The highest CO_2 capture levels of around 5.2 $GtCO_2$/yr are reached in 2050 in 2 DEG and 1.5 DEG scenarios. However, CCS structure differs across scenarios with 1.5 DEG requiring more BECCS to compensate remaining emissions from fossil fuel use and meet the stringent carbon budget. In contrast, in 2 DEG scenarios most CCS is used to retrofit coal and gas-fired power plants. The strong efficiency and circularity push causes a large reduction in the need for deployment of CCS technologies, as shown in Figure 10, where CCS uptake is 84% lower in 2 DEG_CI compared to 2 DEG, as carbon prices are considerably lower. Overall, the model-based analysis shows that reliance on expensive, immature, and risky CCS technologies may drastically decline if the speed of energy transition accelerates, through increased uptake of renewable energy, low-emission cars, electrification, and energy efficiency.

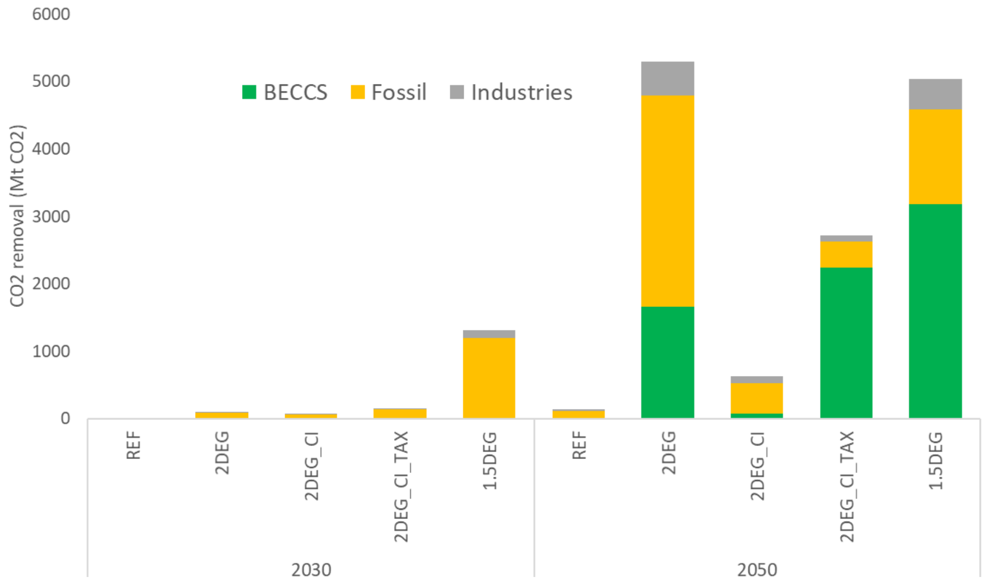

Figure 10. Deployment of Carbon Capture and Storage technologies across scenarios.

3.4. Impacts on investment requirements and energy costs

Ambitious climate mitigation targets drive energy system costs up by inducing additional investment in expensive low-carbon technologies, energy efficiency and zero-emission cars. As shown in [19] and [33], energy system costs generally increase with the level of mitigation effort, driven by increased capital expenditure for low-carbon investment and lower operation costs to purchase energy products driven by lower energy requirements. The cost-optimal 2 DEG scenario results in limited mitigation costs of about 0.5% of global GDP cumulatively over 2025–2050, with the decline in fuel costs partially counterbalancing the increased capital expenditure. The imposition of energy efficiency policies and circularity on top of the climate target would result in higher uptake of efficient—but more expensive—technologies, processes and equipment in the demand sectors, pushing system costs upwards. On the other hand, they lead to reduced carbon price and fossil fuel consumption thus reducing the operating costs. On balance, the adoption of high-efficiency technologies on top of a climate target might increase the overall mitigation costs by 0.2% of GDP relative to the 2 DEG scenario, which is cost-optimal by definition, but is based on a higher carbon price (Figure 11).

Because of the reduced energy demand, the 2 DEG_CI scenario requires the lowest additional supply-side investment among the mitigation scenarios. However, this is more than compensated by increased investment on the demand side, directed to renovation of buildings, uptake of zero-emission vehicles, purchase of efficient appliances and emergence of circular economy in industries. The modelling also shows the potential of the circular economy and lifestyle changes to reduce emissions without posing large additional investment needs. However, high uncertainty surrounds the investment required to implement extreme energy savings and circular economy structures, while energy models cannot capture fully the related investment needs and costs of the circular economy or lifestyle changes [8]. The analysis of socio-economic impacts of decarbonisation requires a detailed representation of energy intensive sectors and a robust estimation of how trade and production patterns will be affected by decarbonisation, which for example drives a switch from internal combustion engines to electric drive trains with ambiguous employment impacts.

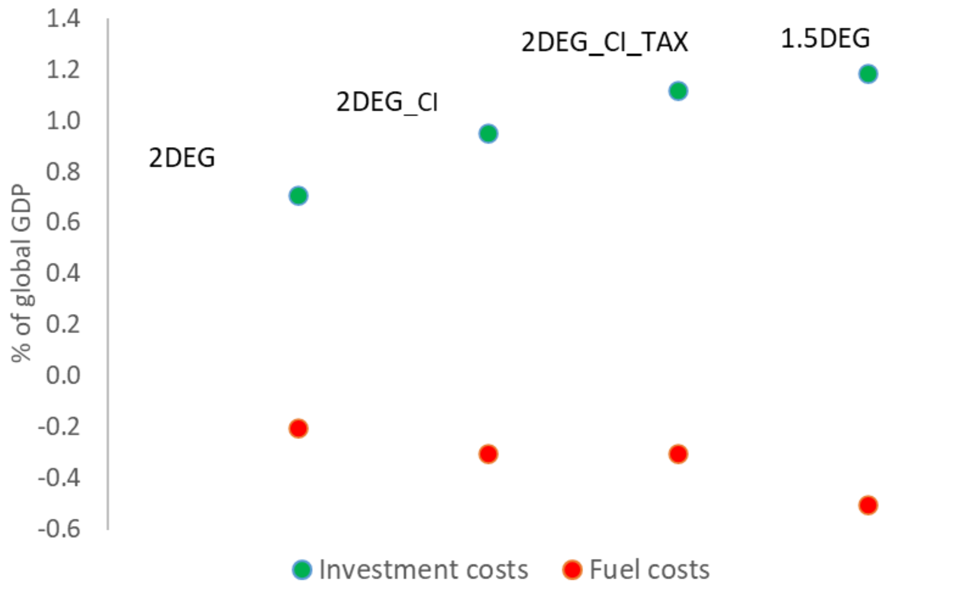

Figure 11. Scenario impacts on global cumulative energy investment and fuel costs over 2025–2050 (in % of global GDP).

4. Discussion and conclusions

The systemic transformation towards deep decarbonisation is a complex process that requires coordinated action by all nations, businesses, citizens, and major emitting sectors. Industrial sectors currently account for more than 25% of global emissions, while most manufacturing processes have a low energy and material efficiency and experience low circularity rates. In recent years, many studies have shown that circular economy can play a large role for the deep decarbonisation required to meet the ambitious Paris goals. However, there is an increasing gap between theory and practice with respect to circular economy strategies. The scenario analysis presented in the current study shows that accelerated energy and resource efficiency improvements coupled with circular economy measures can bring multiple benefits: on the one hand they can stimulate more efficient use of energy and material resources, while reducing the need for high carbon pricing, which may raise social acceptability issues [41]; and they may also reduce the reliance on supply-side investment, especially in expensive and currently immature technologies, such as Carbon Capture and Storage.

The scenarios have been developed with the PROMETHEUS global energy system model, which is enhanced with a representation of circular economy measures, especially in energy-intensive industrial sectors. The scenarios introducing a circular economy structure together with accelerated energy efficiency result in a considerable reduction of energy consumption, driven by changes in sectors manufacturing metals, chemicals, plastics, and non-metallic minerals. Energy efficiency or other ways of limiting energy consumption (circular economy and lifestyle changes) as well as switching to domestically produced low-carbon energy vectors (electricity, hydrogen) can contribute to reducing energy imports, especially in major fossil fuel importers like the EU, China, Japan. Therefore, promoting a circular economy through a smarter use of materials such as plastics and steel can reduce emissions while also contributing to cleaner land, water, and oceans and enhancing security of energy supply, eliminating the exposure of energy importers to geopolitical tensions and import price increases, as shown by the recent unprecedented increases in gas import prices in the EU.

The comprehensive quantification of alternative scenarios with the PROMETHEUS model confirms that circular economy may lead to large emissions reduction in the industry sector resulting in further changes in demand and supply and related investment in all energy system sectors. The circular economy scenario assumes high efficiency improvements in energy end uses combined with an average reduction of physical output for energy-intensive industries of around 10% in 2050 through increased use of scrap steel, higher recycling and reuse rates for plastics, paper and cement, reduced losses of materials, and overall improvements in resource use and material flows. These developments lead to a large reduction of global energy consumption which implies lower needs for investment in expensive and risky supply-side technologies like CCS and lower level of carbon price. Circular economy is a big opportunity to create new markets, technologies and synergies between the energy and industrial sectors by reducing primary raw material needs and developing more re-usable and recyclable products, while promoting economic transformation and creating new high-quality jobs. Therefore, circular economy considerations should be efficiently embedded into climate and sustainable development policies, as CE strategies contribute to meeting global climate goals, while also increasing energy efficiency, enhancing energy security and supporting economic restructuring towards a modern, more sustainable, resilient, low-emission paradigm.

However, full circularity would require significant behavioural changes, large capital investments, changes in the regulatory framework and business model transformation. The transition towards a more energy and resource efficient economy comes with high challenges, including large investment requirements to develop the new energy-efficient technologies and processes, acceleration of technology innovation and the emergence of new business models to exploit the new opportunities from the transition. All these should be combined with changes in consumer behaviour towards less carbon-intensive options with wider acceptance of environmentally friendly lifestyles in everyday decisions. Ambitious and coherent policies should be developed to consistently bring together emissions reductions, energy system transformation and environmental policy (waste, pollution) with industrial policy (e.g., recycling, resource efficiency and new materials) and with research and innovation policy. In this way, policy makers can leverage the synergies between deep decarbonisation targets and other policy priorities (e.g., energy security, economic transformation, resilience), by setting broader goals covering all these dimensions, while exploiting their synergies and minimising potential trade-offs and negative social impacts.

The literature review and the quantitative model-based analysis have shown that low-carbon technology development and deployment combined with circular measures can drastically reduce emissions from the industrial sector towards contributing to the Paris climate goals. The combination of best available techniques in energy efficiency and fuel switching with other options including innovative low carbon production technologies, circular economy, material efficiency, low carbon energy carriers (e.g., green electricity and hydrogen [8]) and CCS. It also requires the full decarbonisation of the electricity sector and the substitution of natural gas by zero carbon gases (e.g., green hydrogen) to the largest degree possible. The industrial transition towards a low-emission, circular paradigm requires a profound alteration of current business models and supply chains, and the development of a systemic approach covering: the sustainable supply of raw materials, optimised material flows in supply chains supporting circular economy and industrial symbiosis, innovative decarbonisation technologies and materials, enhanced energy and resource efficiency and demand-side measures to stimulate the creation and the development of markets for low and zero-carbon products and solutions.

Transforming the linear economy, which has remained the dominant model since the Industrial Revolution, into a circular one is by no means an easy task. Such a radical change entails a major transformation of the current production and consumption patterns, which in turn will have significant impacts on the economy, the environment and society. Understanding these impacts is crucial for climate and industrial policy makers and researchers. This requires developing an in-depth knowledge of the concept of the circular economy, its processes and their expected effects on sectors and value chains as well as the overall impacts on the economy and society. It also requires a dedicated effort to bridge the gap between theory and practice, which appears to be particularly large in circular economy strategies. The current study provides a first attempt to map and quantify the potential contribution of circular economy in the transition to a low-carbon economy. Future research should capture the complex interactions between circular economy and the process of decarbonisation—which are not captured in current modelling frameworks. Moreover, a detailed bottom-up quantification of the costs, potentials and emission savings of various circular economy strategies and the associated challenges is critical to identify opportunities for CE strategies to have the largest impact on mitigation. The financial sustainability of projects and infrastructure related to CE should also be explicitly analysed, while research should identify the sources of green finance that can provide the required resources for the transformation towards a circular economy paradigm. Particular attention should be paid to how the long lifetimes of products, technologies, buildings, and infrastructure influence the transition dynamics towards a circular economy, and how the recycling rates of the raw materials needed for renewable energy and high-tech applications can be increased in order to meet the fast-growing materials demand and increase overall circularity.

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[8] Green electricity refers to electricity produced from zero-emission technologies like renewable energy, while green hydrogen is produced through electrolysis of renewable-based electricity.

grant agreement no. 891943 (WHY project). The information and views set out in this paper are those of the authors and do not reflect the official opinion of the European Commission.

Conflict of interest

No conflict of interest.

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