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Move towards a circular economy and a low-carbon industry—a model comparison approach

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Abstract

The circular economy (CE) has been gaining traction as an effective means to decarbonize the European industrial sector by reducing material demand, especially in the material- and waste-intensive building construction segment. We compare the results of the integrated assessment model IMAGE and the industry sector simulation model FORECAST to analyse the potential contribution of a CE in building construction to industry decarbonization in the European Union until 2050. Both models consistently show that the CE can lead to a reduction of final energy demand between 19% and 47% depending on the model and the sub-sector considered. While both models emphasize the role of electrification and hydrogen for a low-carbon industry, they differ regarding the use of bio-based processes: IMAGE favours bio-based processes with carbon capture, where FORECAST prioritizes electrification and hydrogen. Such different routes have profound implications for the development of the energy supply sector. The high uncertainty surrounding industrial decarbonization scenarios highlights the importance of comparing vastly different models in context of alternative future possibilities and policymaking to improve the understanding of complex systems and prevent overreliance on partial views.

1. Introduction

Beyond its role in response to the broader planetary crisis, the relevance of a circular economy (CE) for the reduction of industrial greenhouse gas (GHG) emissions is increasing due to increasing material extraction on the one hand and the advancing climate crisis on the other (Bashmakov *et al* 2022, UNEP 2024). The basic material industries (i.e. steel, cement and chemicals) are of particular importance as they are responsible for about 20% of emitted GHG in the European Union (EU) (European Environment Agency 2022). The curbing of these emissions is challenging and often very expensive when depending on technological change alone (Worrell and Carreón 2017, Gailani *et al* 2024). Furthermore, the extraction of primary material resources is a driver of other environmental problems including land use change, pollution, and biodiversity loss (UNEP 2024). This renders basic material reduction in the European industrial sector imperative. Thus, CE can play a crucial role in delivering industrial pathways in line with planetary boundaries.

Construction is one of the main consumers of basic materials, such as steel and cement (Cembureau 2023, Eurofer 2023). Buildings Performance Institute Europe *et al* (2023) reported that in 2020 the production of materials for the building construction segment was responsible for around 6% of EU GHG emissions. Beyond GHG emissions, construction and demolition is responsible for the largest waste stream in the EU, i.e. 36% of waste generation in 2022 (Eurostat 2023). In future, material demand and waste generation for building construction might increase due to growing living and service-related spaces (Lotz *et al* 2024b). A CE can potentially decouple virgin basic material from building-related service demand (Lotz *et al* 2024a).

The CE is not a new concept but offers a new framing for strategies increasing resource efficiency (Blomsma and Brennan 2017). These strategies can be categorized according to the 9R framework, which extends the 3Rs (reduce, reuse and recycle) to 9Rs (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover). In detail, these strategies range from the smarter use and the extended lifetime of products to the application of materials, e.g. recycling (Kirchherr *et al* 2017). Various academic and non-academic reports assess the role of a CE to reduce GHG emissions. For instance, Pauliuk *et al* (2021) and Zhong *et al* (2021) highlight material-efficient buildings and cars as a contributor to global GHG emission reduction. Moreover, the Ellen MacArthur Foundation (2019) and the International Energy Agency (2019) outline the contribution of a CE to reducing industry sector GHG emissions related to specific materials, such as steel and cement. At the same time, a CE reduces energy demand, which decreases costs of transformation and alleviates shortages. Accordingly, CE has been gaining traction in EU policy to achieve climate targets while maintaining economic growth (European Commission 2019, European Commission & DG Clima 2019, 2020a).

This paper compares the results of two well-established but vastly different models to analyse the potential contribution of a CE to a low-carbon industry. The models we choose are the integrated assessment model (IAM), IMAGE (Stehfest *et al* 2014) and the energy system model (ESM), FORECAST (Fleiter *et al* 2018). While these models differ regarding their type, sectoral frame, spatial, technological, and geographical resolution as well as level of detail and key input data and assumptions, a basic alignment is realized for the model comparison by implementing a common scenario narrative, harmonizing common input variables, exchanging building stock data, and assessing a common case: CE in EU building construction until 2050. The objective is to use common scenario assumptions to assess the uncertainty related to a CE within a decarbonized industrial system from two different analytical perspectives. This paper aims to address the following question: *Can the application of two different models lead to a holistic understanding of the role of a circular economy in the context of deep decarbonization scenarios, and what are the associated implications on the energy systems?*

1.1. Modelling a CE and a low-carbon industry

Computational models are established tools to provide insights into the long-term development of specific systems and thus contribute to assessments and policy making. Different modelling approaches have been developed to address various issues. IAM and ESM are widely used for simulating the energy demand and GHG emissions of a low-carbon industry (I2AM Paris 2024). Next to these, material flow analyses (MFA) are employed to study material usage and conversion routes in prospective CE scenarios (Corona *et al* 2019). A promising approach to study circularity and its energy implications in a holistic manner is to link IAM/ESM and MFA (Weyant 2017, Deetman *et al* 2020, Daehn *et al* 2024).

IAM aim to represent the interactions between the energy, land, biosphere, and climate systems in an integrated way. Thus, they include the linkages and feedback between these systems. They typically have been used to project energy and land use, and associated GHG emissions over long time scales (2100), as well as explore different pathways aiming towards reducing these pressures (Riahi *et al* 2017). Due to their broad geographic, temporal, and systemic scope, IAM tend to have high levels of technological, societal, spatial and temporal aggregation, compared to more detailed models focusing on single systems. This aggregation, however, limits the insights IAM can provide for assessing specific transformations and detailed elaboration on changes in industrial and material systems.

ESM are established tools to model energy supply or demand (Plazas-Niño *et al* 2022). For the industry sector, simulation and optimization models are available, which either address the complete sector, sub-sectors or specific technologies with high level of technical detail (Fleiter *et al* 2018). The I2AM Paris platform (2024) presents five models for analysing EU industrial decarbonization scenarios. These models, however, are typically focussing on recycling and assess CE based on exogenous assumptions with limited representation of cross-sectoral and cross-system feedback (Fleiter *et al* 2018, Nijs and Ruiz Castello 2019, Schneider and Saurat 2020, Aalborg University 2024, Stockholm Environment Institute 2024).

MFA depict material flows between processes and the accumulation of material stocks (Pauliuk and Hertwich 2016). Stock-driven MFA is particularly useful when analysing future developments as it is less sensitive to fluctuations (Pauliuk and Hertwich 2016, Lauinger *et al* 2021). Considering the secondary material availability is possible by applying dynamic models, which calculate material outflows from the stock (Deng *et al* 2023). Finally, bottom-up models aggregating product-specific flows to material flows allow us to assess changes during product design (Pauliuk and Hertwich 2016). These models, however, lack the computation of energy demand and GHG emissions and particularly, changes due to the transformation of the industrial system.

Kullmann *et al* (2021) highlight that linking MFA with other models could improve the understanding of linkages between energy and material systems. For the case of IAM, this has been implemented for IMAGE (Deetman *et al* 2020, Zhong *et al* 2021). Such IAM-MFA hybrids are increasingly being used to assess scenarios of CE, and the contribution towards reducing GHG emissions (UNEP 2024). For the case of an ESM, Lotz *et al* (2025) show how a MFA can be linked to the industry model FORECAST to assess the contribution of a CE to industry decarbonization. However, only effects within the industry sector are considered.

Building on the available literature, we choose to compare an IAM, and an ESM as both are well-established tools to assess industrial transformation pathways. While IAM are advantageous due to the consideration of system-wide interactions, ESM typically incorporate a higher level of detail regarding industrial processes. Moreover, we favour the use of an IAM and an ESM, which have previously been applied in combination with MFA to exploit their advantages for depicting CE potentials, namely IMAGE and FORECAST.

1.2. Model comparison as a tool to assess future uncertainty

Model comparison is an established tool for guiding policy-making, considering the uncertainty of future developments (Dekker *et al* 2023b, Bistline *et al* 2024). Comparing input data, models and/or results underlines reliability of implications for policy development (Prina *et al* 2022, Henke *et al* 2023). According to a systematic review by Prina *et al* (2022), three types of model comparison studies can be distinguished—each with different objectives and target audience. While the comparison of models with same input data and same or different computational approach sheds light on the impact of resolution or mathematical formulation, the comparison of scenarios resulting from varying input data and models allows to assess commonalities and contradictions. Particularly, the latter is relevant to developing robust policies.

Building on this, we compare vastly different models within the present study, i.e. the IAM IMAGE and an the ESM FORECAST. IMAGE provides a system-wide perspective by integrating energy, land, and material flows, whereas FORECAST offers detailed process-level representation of industrial technologies. Their vast differences, particularly with regard to endogenous and exogenous drivers, make them well suited to understand future uncertainty of industrial decarbonization scenarios and guide policymaking.

2. Method and data

2.1. Models

The two models applied within this study are the IAM IMAGE and the industry sector simulation model FORECAST. These models were chosen as they have been applied in combination with MFA, and provide vastly different perspectives on related research questions. Table 1 provides a structured overview of these models and their characteristics, while Annex A.1 includes a detailed description. IMAGE has the advantage of covering interactions within the energy system, and FORECAST analyses the industrial sub-sectors at a country- and process-specific basis. Thus, the models complement each other regarding their key limitations. IMAGE is limited to an aggregated coverage of industrial sub-sectors, neglecting individual products. FORECAST, in contrast, does not integrate the energy supply perspective endogenously but determines the deployment of new processes exogenously. Also, the linkage with the MFA differs between the two models. In IMAGE, the MFA determines material demand for relevant capital stocks endogenously, while a stock-driven MFA limited to buildings is soft-linked with FORECAST.

Common input variables were harmonized, enabling comparability between the models. However, over-restricting the models to produce identical results by exogenous determination of otherwise endogenous variables was avoided to allow them to capture model-specific results. The common drivers for the models are gross domestic product (GDP) and gross value added (GVA). But there are differences regarding energy prices and industrial production, as these are determined endogenously in IMAGE and exogenously in FORECAST. Moreover, a data exchange was established between the MFA modules. The residential building stock was modelled endogenously in IMAGE, and then provided as input for the stock-driven MFA linked to FORECAST. Finally, IMAGE and the building MFA connected to FORECAST aligned their assumptions for CE measures in nearly all cases. However, due to the different model logics, it was not possible to use completely identical parameters. In summary, this means that only model inputs and not the outputs were aligned, which is useful to depict the commonalities and contradictions between future scenarios.

Table 1. Model overview.

	IMAGE (van Sluisveld <i>et al</i> 2021)	FORECAST (Fleiter <i>et al</i> 2018; Lotz <i>et al</i> 2025)
<i>Purpose</i>	Assess interactions between human and natural systems; explicit representation of energy supply and demand as well as the agricultural system, impact and feedback represented through resource availability and depletion, crop growth, nutrient cycles, GHG emissions and climate change	Develop scenarios for the long-term development of future energy demand and GHG emissions of the industry sector considering a broad range of mitigation options and a high level of technological detail
<i>Approach</i>	Recursive dynamic simulation, soft-linked to an MFA	Bottom-up, process-specific simulation, soft-linked to MFA
<i>Calibration</i>	Energy balances of the International Energy Agency (IEA, 1971–2018) for global calibration of energy demand and supply. Statistics of the Food and Agricultural Organization (FAOSTAT) for agricultural demand and production. Multiple other datasets for specific or regional indicators	EUROSTAT energy balances for the energy demand. National emission inventories according to the United Nations Framework Convention on Climate Change (UNFCCC) for GHG emissions
<i>Main inputs</i>	Population. Economic development (i.e. GDP, sub-sectoral GVA). Assumptions on behavioural and technological change. CO ₂ price, climate target, or other policy measures	Process characteristics (i.e. energy demand). Economic development (i.e. GDP, sub-sectoral GVA). Industrial production (partly linked to MFA, including exogenous assumptions on deployment of new production processes). Energy and CO ₂ prices
<i>Main outputs</i>	Material demand. Energy demand. GHG emissions. Land cover	Energy demand. GHG emissions
<i>Spatial</i>	26 world regions, including Western and Central Europe	National level for the 27 member states of the EU and the United Kingdom
<i>Sectoral/ technical</i>	Materials for buildings, electricity infrastructure, and transport. Five sectors, including industry and industrial sub-sectors. Iron and steel: blast furnace, electric arc furnace, electrowinning, direct reduction with natural gas or hydrogen. Non-metallic minerals: Clinker calcination, cement grinding, carbon capture and storage. Chemicals: Naphtha-based steam cracker, natural gas-based production of methanol and ammonia, methanol-based ethylene production, hydrogen-based production of methanol and ammonia	Industrial sub-sectors. Iron and steel: blast furnace, electric arc furnace, direct reduction with natural gas or hydrogen. Non-metallic minerals: Clinker calcination, cement grinding, carbon capture and storage. Chemicals: Naphtha-based steam cracker, natural gas-based production of methanol and ammonia, methanol-based ethylene production, hydrogen-based production of methanol and ammonia
<i>Time</i>	1970–2100, yearly steps	1990–2050, yearly steps

2.2. Scenarios

We define two scenarios for our analysis: A reference (Ref) scenario, and a CE scenario. The Ref scenario reflects the ambitious decarbonization targets put forward by the EU, i.e. GHG emission reduction by at least 55% in 2030 and 90% in 2040 compared to 1990 (European Commission 2020b, 2024). The CE scenario extends the Ref scenario by enforcing ambitious CE measures in buildings, based on Lotz *et al* (2024a).

While maintaining consistent narratives, the detailed implementation of these scenarios in the two models differs reflecting their inherent differences described above, particularly the endogenous or exogenous determination of framework conditions and technology deployment. Thus, the choice for a single ambitious CE scenario was made to ensure comparability across the two structurally different models.

For IMAGE, the Ref scenario combines population and GDP trajectories from the Shared Socioeconomic Pathway ‘middle of the Road’ (SSP2) with a linearly increasing carbon price, which reaches 400 \$/t CO₂ in 2050 (same as the *DIAG-C400-lin* scenario in Dekker *et al* 2023a). Energy prices

Table 2. Circular economy scenario settings based on Zhong *et al* (2021) and Lotz *et al* (2024a).

	IMAGE	FORECAST
<i>Reusing building elements</i>	Not incorporated	Reuse share of 38% in the building MFA
<i>Reusing structural steel</i>	Not incorporated	Reuse share of 6% in the building MFA
<i>Recycling</i>	Full exploitation of steel recycling potentials (depending on the scrap availability, determined through stock modelling). Recycle 70% of plastics and chemicals available at end-of-life	Steel scrap not recycled for buildings is available for recycling for other end use sectors
<i>Extending building lifetime</i>	Increased building lifetimes by 20% from baseline	Building demolition is reduced by 30% in the building MFA
<i>Reducing the floor space</i>	Floor space per capita is limited to 35 m ² in residential buildings. Households with higher floor space converge to this value over 30 years.	Residential building stock from IMAGE as input for the building MFA
<i>Shift in housing types</i>	Shift to housing types with lower material use intensities (i.e. apartments)	Residential building stock from IMAGE as input for the building MFA
<i>Sharing building systems</i>	Increased ‘sharing’ of building systems, including appliances, cooking facilities etc.	Residential building stock from IMAGE as input for the building MFA
<i>Material-efficient design</i>	Include lightweighting and substitution of materials	Reduced material intensity by 41% in the building MFA
<i>Timber construction</i>	Not incorporated	Timber-based building archetypes in the building MFA
<i>Reducing clinker share</i>	Reduced average clinker share to approximately 0.7	Reduced European average clinker share to 0.7
<i>Low-carbon cement</i>	Not incorporated	Up to 10% low-carbon cement types

are determined endogenously based on changes in supply and demand. Behavioural and efficiency choices are driven by the energy prices. No further policies are considered in this scenario.

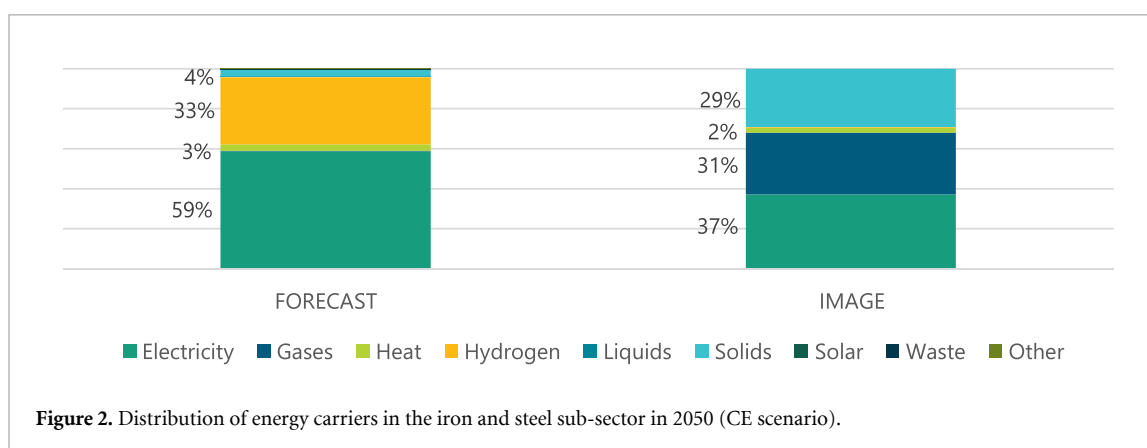
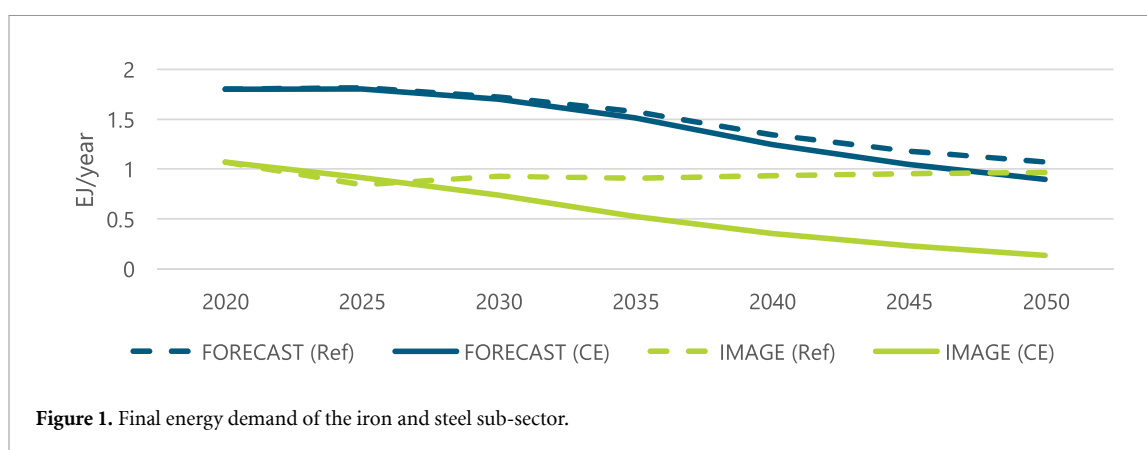
Since FORECAST focusses on the industry sector, several exogenous assumptions on framework conditions are required that are endogenous in IMAGE. The baseline for the economic development and the industrial production in the Ref scenario is the EU reference scenario (European Commission 2021). Further scenario assumptions are described in detail by Zakeri *et al* (2025). In short, energy prices are assumed to remain constant or increase slightly, except for the biomass price, which increases significantly. Also, the scenario is characterized by a high carbon price. Moreover, the scenario assumes that necessary infrastructure for electricity, hydrogen, and carbon is available. Carbon capture technologies are limited to otherwise unavoidable emissions (i.e. clinker and lime production).

To consider a comprehensive CE, in line with the 9R framework (Kirchherr *et al* 2017), we build on the systematic literature review conducted by Kochanski *et al* (2024). In detail, we assess up to eleven specific CE measures in the CE scenario considering the models’ capabilities for implementation (see table 2 below). IMAGE focusses on seven CE measures based on Zhong *et al* (2021). In contrast to FORECAST, IMAGE considers both steel and plastic recycling, while FORECAST is limited to steel recycling. To this end, FORECAST considers four additional CE measures. The parametrization of these measures is determined by a literature review and expert interviews, presented by Lotz *et al* (2024a).

2.3. Comparison method

For the comparison, we focus on the resulting energy demand and energy carriers from the two models, to assess the role of a CE in a decarbonized industrial system. We rely on two core premises:

- The **start value** should be close to identical between models, as it reflects current statistics and production technologies. In case of significant differences in start values among the models, these cannot be caused by the models themselves, but rather by differences in model calibration, sectoral/spatial resolution or data sources.
- The **end value** as well as the **trend** between the start and end value are calculated by the models, hence they are dependent on the (exogenous) scenario definition as well as (endogenous) model-specific features, such as technology portfolio, rate of diffusion of technologies or efficiency improvements.

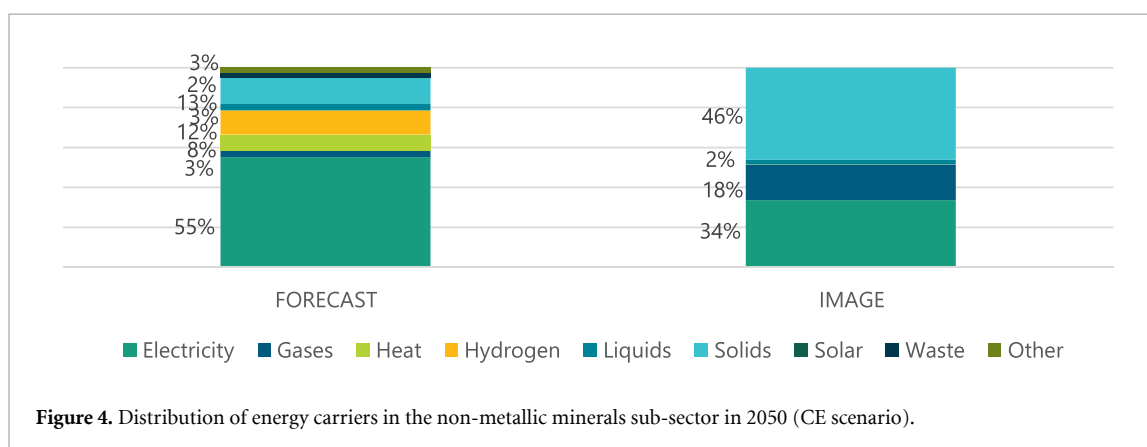
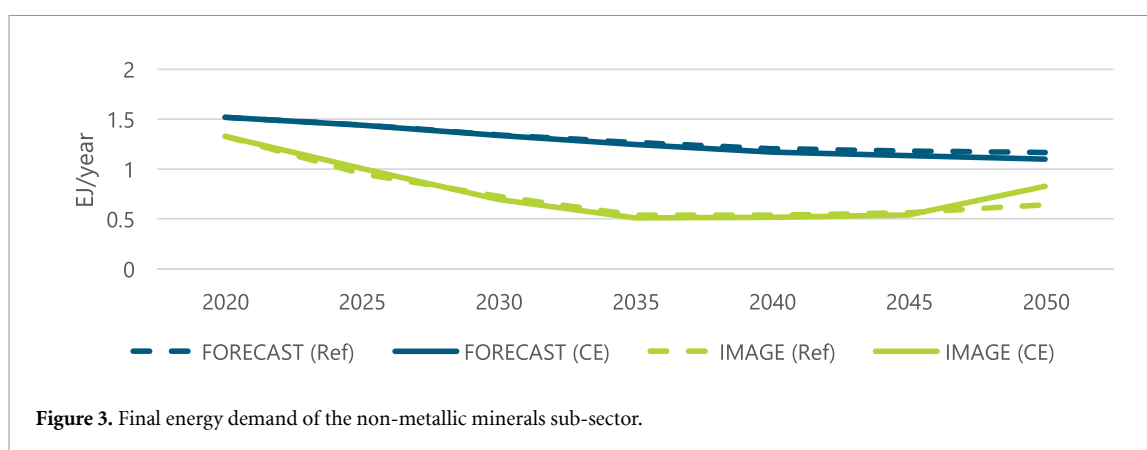


3. Results

The output of the two models employed in this study contains many results that are relevant for analysing the impact of the CE on decarbonization. We focus on the final energy demand (FED, excluding feedstocks) in the three industrial sub-sectors, which are affected by the considered CE measures, namely iron and steel, non-metallic minerals as well as chemicals. Note that, in particular, the analysis of the chemicals sector reveals differences, which can be attributed to varying sectoral definitions and CE scenario settings.

3.1. Iron and steel

Figures 1 and 2 present the results for the final energy demand in the iron and steel sub-sector. Figure 1 shows the temporal profile of the total FED between 2020 and 2050, and the latter the distribution of energy carriers in the year 2050. When comparing the total FED calculated by the models in both scenarios, it becomes apparent that IMAGE comes to a significantly lower start value than FORECAST. This is caused by a different sub-sectorial definition. In detail, IMAGE does not consider the FED to produce coke, used in the emission-intensive primary production of steel in the blast furnace. This is, however, considered by FORECAST. Also, the end value differs considerably in the CE scenario. This can be explained by the main route for carbon-neutral primary steel production. While IMAGE relies on electrowinning, FORECAST considers the direct reduction of iron ore with hydrogen, in combination with the electric arc furnace. Electrowinning is characterized by a higher energy efficiency. However, this technology has a lower technology readiness level (Humbert *et al* 2024), which is why this technology option is excluded in FORECAST for the modelled timeframe. Both models show a trend of reducing FED between 2020 and 2050, ranging from up to 50% for FORECAST and up to 88% for IMAGE in the CE scenario. In IMAGE, the decline in FED is caused by the increased energy efficiency of electrowinning compared to current steel production technologies, outweighing increasing production quantities. Despite a CE in buildings, the endogenously determined steel production quantities are increasing in the CE scenario in IMAGE. This is contrasted by FORECAST, which exogenously assumes decreasing production quantities—both for the Ref and the CE scenario. Thus, the decline in FED is caused by a combination of the decreasing production quantities and increased energy efficiency of steel production.



The difference between the main primary steel production routes is also visible when comparing the energy carrier distribution for the CE scenario in 2050 in figure 2. Both models show a strong focus on electrification. For IMAGE, the role of electrification in steel production is underrepresented in the figure below, as electricity is much more efficient than the use of other fuels. Although solids and gases remain in use, they constitute only a minor share and largely persist due to slow stock-turnover and inertia in investment decisions. In FORECAST, electrification plays a significant role, due to a significant share of electricity-based secondary production in the electric arc furnace. For primary production, the use of hydrogen is focused upon in FORECAST.

3.2. Non-metallic minerals

Figures 3 and 4 present the results for the FED in the non-metallic minerals sub-sector. Figure 3 shows the FED between 2020 and 2050. When comparing the model results, it is visible that both models have a comparable start value. The minor deviation in the year 2020 can be explained by the use of different data sources: While IMAGE was calibrated to energy balances of the IEA, FORECAST is calibrated to EUROSTAT energy balances and statistical production data. The IMAGE results show a lower end value and different course compared to FORECAST in both scenarios. This difference can be traced back to the production quantities, which are determined endogenously by IMAGE. In the IMAGE projections, the prescribed CO₂ price requires massive electrification of energy services, leading to associated increases in electricity infrastructure, and thus demand for cement. Consequently, the demand for non-metallic minerals stagnates/grows after declining until 2035, outweighing the contribution of a CE in buildings to reduce material demand. Such a link between infrastructure and material demand is not considered within FORECAST. In line with this, the FED decreases by up to 28% (FORECAST) or 38% (IMAGE) in the CE scenario. In both models, the timely course of FED correlates with production quantities, considering energy efficiency improvements. However, in IMAGE the FED for non-metallic minerals increases slightly after 2045 in the CE compared to the Ref scenario, despite lower production quantities. This is caused by increasing competitiveness of biomass (especially in combination with carbon capture) in the presence of high CO₂ prices, which is related to a lower efficiency than other energy carriers.

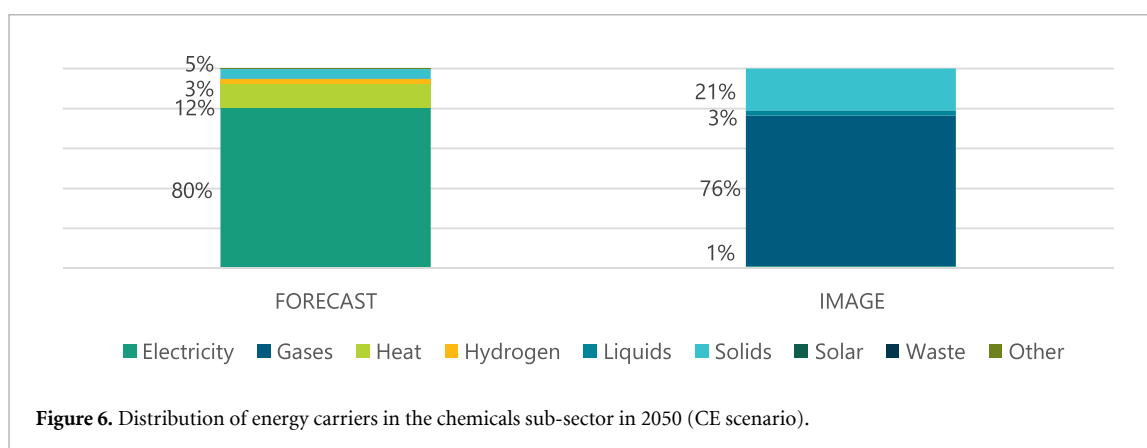
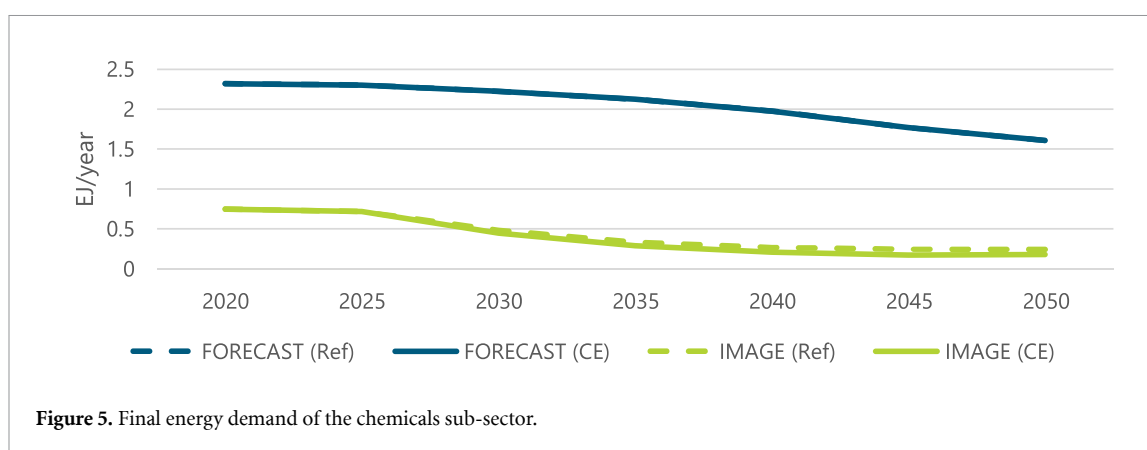


Figure 4 presents the distribution of energy carriers in 2050. In contrast to iron and steel, there is no fundamental difference between the considered production technologies, i.e. kilns with carbon capture. The energy carrier mix resulting from IMAGE is different from that of FORECAST, due to a strong focus on solids and gases in the former model. In detail, IMAGE prioritizes solids and particularly biomass produced from agricultural residues, as this leads to negative emissions when captured, which compensate residual emissions from other sectors (Daioglou *et al* 2019, Hanssen *et al* 2020). These intersectoral dynamics are not captured by FORECAST, which limits the use of biomass in the industry sector due to the potentially limited sustainable availability, and the use in other sectors (e.g. mobility). This is, however, a scenario assumption and—as FORECAST is a sectoral model—not an endogenous model result.

3.3. Chemicals

Figures 5 and 6 show the results for the FED (excluding feedstocks) in the chemicals sub-sector. Figure 5 shows the temporal profile between 2020 and 2050, and the latter the distribution of energy carriers in 2050. When comparing the FED by the models, it becomes apparent that IMAGE comes to a significantly lower start value. This difference can only be explained by a different sectoral definition. FORECAST is calibrated to EUROSTAT energy balances and historical production quantities. The IMAGE numbers include the electricity and heat used during the conversion process of primary feedstocks to chemicals and plastics (including fertilizer production), as explained in Daioglou *et al* (2015). This is calibrated to total non-energy use, as reported by the IEA (gross, including feedstocks). Due to the lower start value, also the end value in IMAGE is lower than in FORECAST, for both scenarios. Also, the reduction compared to the start value is significantly higher in IMAGE with around 76% compared to 31% in FORECAST in the CE scenario. Overall, the impact of a CE in buildings on the chemicals sub-sector in IMAGE primarily shows the effect of increased recycling, which is not considered by FORECAST. Consequently, the impact of the other measures is minor.

Further differences are visible when comparing the energy carrier mix in figure 6. While IMAGE relies on mostly on gases and solids, FORECAST shows a strong focus on electrification. Similar to the non-metallic minerals sector, IMAGE prioritizes negative emissions, while FORECAST limits the use of biomass.

4. Discussion

Despite using two vastly different models that yield diverging results, we are able to identify commonalities. While it must be highlighted that the scenarios assume fundamental changes in production and consumption patterns, requiring a strong policy framework, our comparison confirms a well-established insight: the CE has the potential to reduce material and energy demand. A lower overall demand for final energy services contributes to the achievement of climate targets, as it effectively decreases the size of the energy system, hence—even without changes in the energy mix—leads to smaller amounts of GHG emitted into the atmosphere. Additionally, this aligns well with the EU target to significantly increase energy efficiency in all sectors (Energy Efficiency Directive [2023/Directive \(EU\) 2023/1791](#)). The value of our findings lies not in revealing this, but in showing that vastly different models reach this conclusion, despite divergent underlying assumptions, highlighting the robustness across modelling paradigms. Future research should extend this work by analysing alternative scenarios for different levels of ambition in a CE.

However, the contradictions between the two models also provide valuable insights, as they complement each other. Our detailed comparison of the long-term energy carrier mix in the industrial subsectors iron and steel, non-metallic minerals, and chemicals reveals that while emphasizing the role of electrification and hydrogen, the two models implicitly or explicitly assume very different underlying energy systems. IMAGE endogenously favours the use of bio-based processes accompanied by carbon capture technologies, as these can realize net negative emissions, which are then used to compensate for residual emissions elsewhere in the energy system. In contrast, FORECAST lacks systemic perspective, hence favours electrification and hydrogen deployment, exogenously assuming limited availability of biomass. These differences highlight how different model paradigms influence scenario results, highlighting the importance of multi-model comparison.

These results emphasize alternative possibilities for the future development of the European industrial sector, which could essentially continue using traditional types of fuels, if they are accompanied by carbon capture, or switch to alternative carriers altogether. Such different routes depend on cross-sectoral integration and the role of industry in overall decarbonization, while having profound implications for the development of the energy supply sector. In particular, the widespread use of electricity and (green) hydrogen projected by FORECAST would entail a massive growth of the power sector, as well as a major shift towards green hydrogen production in the fuel supply sector. Future research should explore these possibilities and their implications for industrial and climate policy in more detail, for example, by analysing scenarios in which the use of certain energy carriers in specific industrial subsectors is exogenously constrained.

The findings underscore the importance of comparing results from vastly different models. While the comparability of IMAGE and FORECAST may be limited due to some aspects, in particular their sub-sectoral definition and scenario-specific set-up, there are two takeaways. Firstly, comparing model results can improve the understanding of complex interlinkages and systems. Secondly, relying on results from a single model is problematic, as it provides only a partial view. Thus, comparing the two models contributes to a more holistic understanding of a CE and a low-carbon industry. This calls for more cross-scale model intercomparisons and further exploration of possible linking of such models, in order to take advantage of the strong points of different modelling paradigms in future studies.

While these findings carry important implications for the interpretation of a CE in vastly different models, it is equally important to recognize the uncertainties inherent in each model. While the projections of IMAGE account for systemic changes to meet climate targets, this may include structural biases that affect the generalizability of the results. FORECAST, in contrast, relies on exogenous definitions of systemic conditions, limiting its adaptability. Both models are sensitive to input parameters and scenario assumptions, particularly the economic development and prices, which constrains the robustness of the results. Future research should systematically examine these uncertainties and structural assumptions, for example by conducting sensitivity analysis of input parameters and implementing multiple alternative scenario definitions. Such efforts would enable a more rigorous assessment of the potential impact of CE on the future European industrial sector.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Supplementary Data available at: <https://doi.org/10.1088/2515-7620/ae95c6/data1>.

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Appendix. Model description

A.1. IMAGE

IMAGE is a comprehensive ecological-environmental model framework that simulates the environmental consequences of human activities worldwide. A graphical overview of the model is shown in figure 7 below. It represents interactions between energy, land, biophysical, and climate systems to assess sustainability issues such as climate change, biodiversity, and human well-being. The objective of the IMAGE model is to explore the long-term dynamics and impacts (up to 2100) of global changes that result from interacting with socio-economic and environmental factors.

The model identifies socio-economic pathways, and projects the implications for energy, land, water, and other natural resources, subject to resource availability and quality. Unintended side effects, such as emissions to air, water and soil, climatic change, and depletion and degradation of remaining stocks (fossil fuels, forests), are calculated and taken into account in future projections.

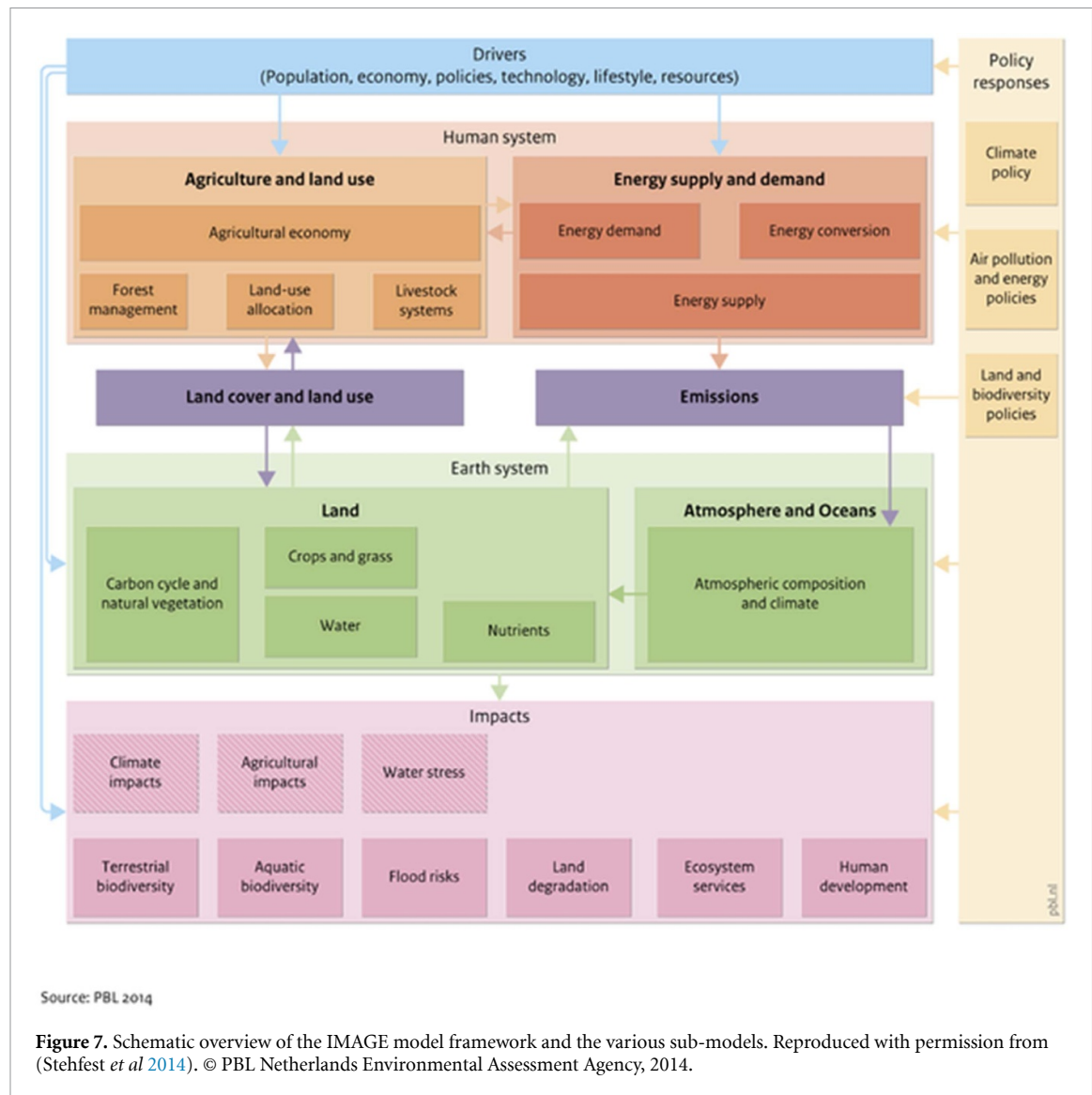
IMAGE follows a recursive dynamic solution method and thus classifies as a simulation model. That is, changes in model parameters are calculated on the basis of information from the previous time-step, lacking foresight. The model includes a detailed description of the energy and land-use system and simulates most of the socio-economic parameters for 26 regions and most of the environmental parameters on the basis of a geographical grid of 30 by 30 min or 5 by 5 min (depending on the variable).

Important inputs to the model are descriptions of the future development of so-called direct and indirect drivers of global environmental change. Exogenous assumptions on population, economic development, lifestyle, environmental and technology policies, and technology change.

The energy system is represented by the energy-system simulation sub-model, TIMER (van Vuuren *et al* 2007). This energy model includes fossil and renewable primary energy carriers (coal, heavy/light oil, natural gas, modern/traditional biomass, nuclear, concentrated/photovoltaic solar, onshore/offshore wind, hydropower, and geothermal). Primary energy carriers can be converted to secondary and final energy carriers (solids, liquids, electricity, hydrogen, heat) in order to provide energy services for different end-use sectors (heavy industry, transport, residential, services, chemicals and other).

The model projects future (useful) energy demand for each end use sector based on relationships between energy services and activity, the latter of which is related to economic growth. For details on method by which the energy demand of each sector is modelled please refer to van Ruijven *et al* (2016) (heavy industry), Girod *et al* (2013), Girod *et al* (2012) (transport), Daioglou *et al* (2012) (residential), Daioglou *et al* (2014) (chemicals) and Stehfest *et al* (2014) (other sectors).

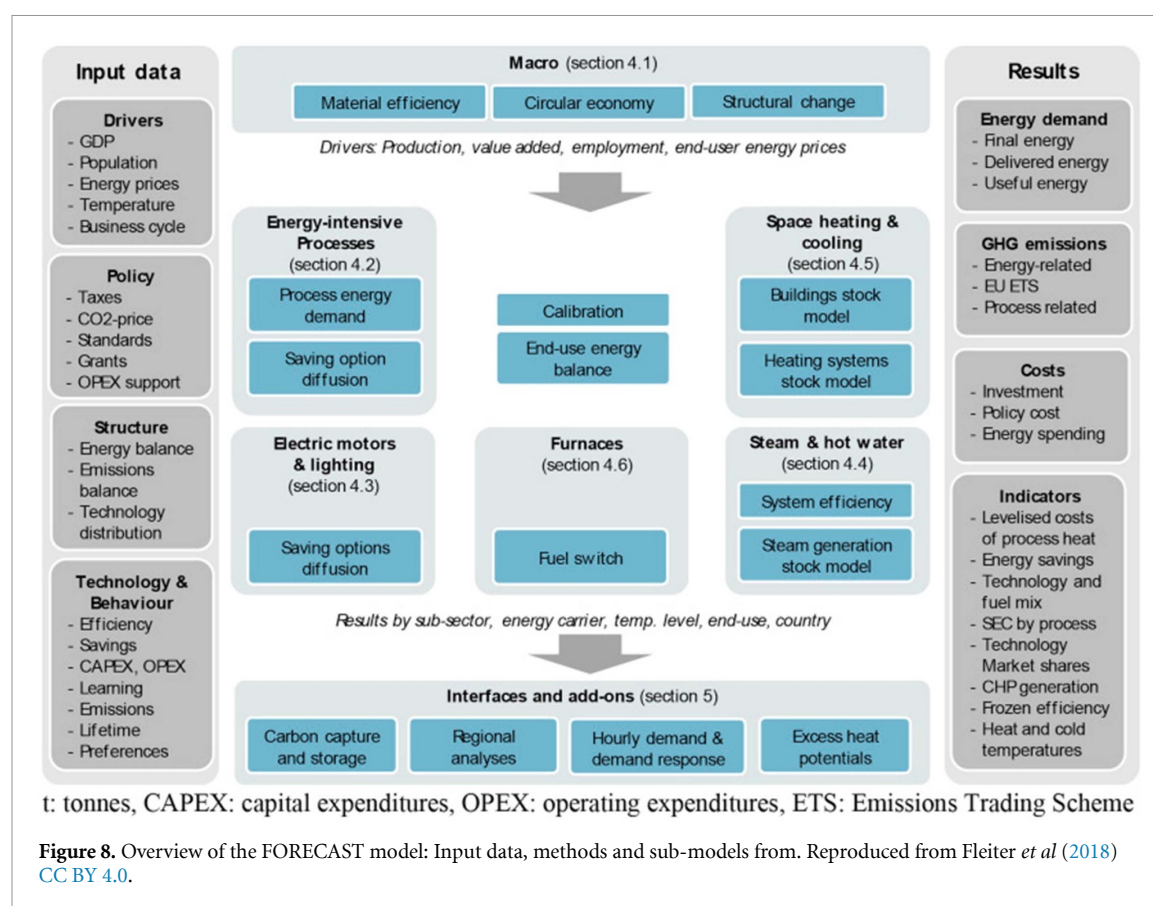
For each demand sector, secondary energy carriers (including solid and liquid biofuels) compete based on relative costs with each other in order to meet the useful energy demand. A multinomial logit function is used to determine market shares of each energy carrier, where the cheapest option gets the



largest market share, the second cheapest the second largest market share, and so on. Energy prices are based on supply curves of energy carriers (Rogner 1997, Mulders *et al* 2006). For non-renewable sources, these are formulated in terms of cumulative extraction; while for renewable sources, these are formulated in terms of annual production (as explained above for biomass).

A.1.2. Forecast

The FORECAST energy demand model was developed for the analysis of scenarios on the future development of industrial GHG emissions and energy demand in the EU 27, United Kingdom, Switzerland and Norway. It makes it possible to evaluate different framework conditions for economic development (GDP, population, energy prices) as well as the techno-economic characteristics of energy conversion technologies on the energy demand side (see figure 8). The FORECAST simulation model is methodologically based on a technology-specific bottom-up approach that links the future development of energy consumption and GHG emissions with technological developments in the industry sector. This approach makes it possible to consider technological trends and their effects on the dynamics of energy consumption. On the other hand, it allows conclusions to be drawn about the closeness of the energy scenarios to reality, since each scenario is based on a specific technological development. The FORECAST model considers the industrial sectors according to national energy balances at the final energy level (Fleiter *et al* 2018, Rehfeldt *et al* 2018).



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