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A race to zero - Assessing the position of heavy industry in a global net-zero CO_2 emissions context

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ABSTRACT

In this study, we explore the decarbonisation pathways of four carbon and energy-intensive industries (respectively iron & steel, clinker & cement, chemicals and pulp & paper) in the context of a global 2050 net-zero carbon emissions objective using the IMAGE integrated assessment model. We systematically test the robustness of the model by studying its responses to four different decarbonisation narratives and across six different world regions. The study underpins earlier conclusions in the literature on 'residual emissions' and 'hard-to-abate sectors', such as the persistence of residual emissions and the overall continued use of fossil fuels by heavy industries within the global 2050 net-zero context (with the pulp & paper sector as an exception). However, under the condition that net-negative emissions are achieved in the power and energy conversion sectors prior to the 2050 landmark, the indirect emission removals can compensate for the residual emissions left in the industry sectors, rendering these sectors 'net-zero' as early as the 2040s. Full decarbonisation of industrial (sub)sector(s) is found to be possible, but only under very specific narratives and likely outside of the 2050 timeline for the iron & steel, clinker & cement and the chemical sector. Subsequently, we find that the decarbonisation patterns in IMAGE are industry and regionally specific, though, different strategic considerations (narratives) did not substantially change the models' decarbonisation response before or after 2050. Important aspects of the decarbonisation responses are the (direct and indirect) electrification of the iron & steel sector, a full dependency on carbon removal technologies in the clinker & cement sector, the closing of carbon and material loops in the chemical sector and zero-carbon heating for the pulp & paper sector. However, further research and modelling efforts are needed to study a broader palette of conceivable decarbonisation pathways and implications for industry within a global 2050 net-zero economy context.

1. Introduction

Worldwide efforts are needed to limit global mean temperature increase to well below 2° Celsius (2°C) relative to pre-industrial levels and preferably closer to 1.5° Celsius (1.5°C) [61]. The United Nations' Intergovernmental Panel on Climate Change (IPCC) has indicated in its special report on 1.5°C (SR1.5) that reducing global net anthropogenic carbon dioxide (CO_2) emissions to zero by 2050 is considered consistent with the lower bound of the 1.5°C Paris climate ambition [25]. Although many transition perspectives are represented in the SR1.5 [53], it features only little information about how the heavy industry (an umbrella term used to describe a variety of energy and carbon-intensive industrial subsectors) could contribute to this objective.

State-of-the-art projections in the SR1.5 describe, for example, that total global carbon emissions in the industry sector need to drop by 50%-93% in 2050 compared to 2010 levels to stay in line with the 1.5°C Paris climate objective [23]. On a regional level, if one looks at the results within the 10^{th} to 90^{th} percentile, one will find that the presented emission reductions range from a 25% increase (found in projections for the Middle East and Africa) to a 99% decrease (found in projections for Latin America) in carbon emissions. This bandwidth leaves a lot of room for interpretation on the needed decarbonisation efforts on an industrial subsectoral level [7,38,58]. As a result, and in the absence of a coordinated policy response towards reaching the Paris climate objective for industry [1,27], much of the climate activities in this sector revolve now, for a large part, around formulating "net-zero ambitions" towards 2050

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by major (industry) stakeholders themselves. Examples of this are found for the cement [22], steel [3,59] and (petro)chemical [2,6,54] sectors. Some ambitions are accompanied by detailed roadmaps stipulating how this can be achieved [3][74].

A significant knowledge gap concerns whether these subsectoral ambitions are appropriate within the context of the Paris Climate Agreement objective, which is also structurally recognized in science, policy and the corporate environment [55,71]. Consequently, in this study, we attempt to fill this gap by unpacking the industrial response strategies that underpin the macro-perspective as published in the SR1.5. We specifically choose to focus on the IMAGE integrated assessment model [57] as this model includes an explicit representation of several industrial subsectors and their value chains in its model structure as opposed to other IAMs (see, e.g. Edelenbosch et al. [16] for a broader overview). Secondly, we limit our scope to the top four carbon and energy-intensive industries (respectively iron & steel, clinker & cement, chemicals and pulp & paper) that together make up 75% of the total current direct industrial emissions [24] and analyse their responses on a (1) sectoral, (2) temporal and (3) regional scale. As various strategic considerations are being addressed for industry in terms of technological and consumption change [18], we have developed four archetypical decarbonisation narratives that reflect these options and use them to explore their consequences at the global and regional scale.

Section 2 elaborates on how industry is represented and what suite of decarbonisation options is included within the IMAGE integrated assessment model. Subsequently, Section 2 also introduces the four industrial decarbonisation narratives used in this study. Section 3 presents the results of the assessment. Sections 4 and 5 discuss and conclude.

2. Methods

2.1. Model

To explore the potential and implications of industrial change in a broader context, we apply the IMAGE integrated assessment modelling framework [57]. IMAGE is an energy-economy-environment modelling framework that simulates the interactions between society, the biosphere and the climate system. The IMAGE modelling framework is designed in such a way that it allows the exploration of long-term dynamics and the impacts of global changes that result from interacting socio-economic and environmental factors. The framework consists of various system-dynamic submodels that can emulate historical and potential future responses through specific pre-defined (techno-economic) rule sets and constraints on (economic) activity.

One of the submodels in the IMAGE modelling framework is a recursive-dynamic energy system model (Van Vuuren et al., 2011). This energy system submodel can describe the annual demand and supply of different energy carriers for a set of 26 world regions (regional classification can be found online at pbl.nl [51])[1] and for multiple represented economic sectors (including industry). The IMAGE models' general workings are framed around dynamic price-based merit orders for energy carriers, services and technology choices. The merit orders are determined by multiple multinomial logit (MNL) formulations that are applied throughout the model, each accounting for differences in relative costs and various context factors per option (Van Vuuren et al., 2011). As a result, the IMAGE model includes dynamic formulations for e.g. renewable energy sources [11], biomass yields, uses and limitations [8], CCS [35] and hydrogen [64], amongst others, with endogenous processes that compute, for example, the price and availability of these resources across the whole modelled system.

For industrial services and technologies, the IMAGE model includes representations for the iron & steel, clinker & cement, chemicals and pulp & paper sector [9,65,67]. Socio-economic drivers define the total consumption of basic materials per capita, and total production always meets the total consumption each year. Simple vintage stock models are applied throughout the IMAGE model, with an exception for the chemical sector, to represent the changes in production capacity. Decision-making for production capacity is based on the current stock in place and the costs of implementing new production capacity (accounting for capital expenditures, operational expenditures and contextual parameters like policy costs). As global models look at averages (and not site or lifecycle specific details), it leads to a gradual response over the estimated lifetime of a production system. The IMAGE model also includes simple representations of material recovery and recycling systems in the iron & steel, chemical and pulp & paper sector to take 'downstream' value chain effects and feedbacks into account. Additionally, an explicit representation of material stocks is available for the iron & steel sector value chain (comprising of buildings, cars, machinery, packaging) and the pulp & paper sector (comprising of paper and paperboard applications).

As the industrial subsector representations are all different and unique to the IMAGE model, we will elaborateon the specifics per industry in more detail in the following sections. For a more comprehensive documentation we refer the reader to annex A of the supplementary information (SI).

2.1.1. Iron & steel industry

The iron & steel industry representation in the IMAGE model framework includes a cradle-to-cradle value chain for iron to steel production and use. Thirteen different existing and innovative steel production routes are formulated in the technology portfolio (see Annex A-a in the SI for a breakdown). Decision-making for production capacity is based on the current stock in place and the costs of implementing a new production route (using annualized fixed and variable costs). Steel demand is allocated over four different product groups (e.g. buildings, machinery, cars and packaging) [65]. Lifetimes for production capacities are set to 30 years. Steel applications have variable lifetimes and are normally distributed around an average lifetime with a standard deviation. End-of-life options are included, such as scrap recycling.

2.1.2. Clinker & cement industry

The clinker & cement industry representation in the IMAGE modelling framework includes a cradle-to-gate value chain of clinker and cement production. Clinker and cement production are represented via a stylised representation of a system operating a dry rotary lime kiln. Four different kinds of rotary lime kiln options are included which differ in energy and carbon efficiency. Subsequently, lime kilns can be powered by different energy carriers (mainly fossil fuel, biomass and electricity). Decision making for production capacity is based on the current stock in place and the costs of implementing a new production route (using annualized fixed and variable costs) [65]. Lifetimes for production routes are set to 25 years. No explicit end-use applications are modelled (e.g. buildings and construction) nor specific end-of-life processes. Some process integration is assumed via the use of blast furnace slag and fly ash from the power sector as an alternative binder to Portland cement clinker [32].

2.1.3. Chemical industry

The IMAGE model framework includes a cradle-to-cradle value chain representation for the chemical industry [9]. Although multiple chemical conversion routes are represented (including high-value chemicals, methanol, ammonia and refinery products), we focus here on the "high-value chemical" (HVC) subsection of the model (reflecting olefins and aromatic hydrocarbons). The model includes a representation of 9 conversion routes for high-value chemicals, including five primary conversion routes (using fossil and biobased feedstocks) and three secondary conversion routes (utilizing waste, black liquor or CO_2 as a feedstock). Production capacities are not explicitly modelled but implicitly included in the parameterisation of the represented

[1] https://models.pbl.nl/image/index.php/Region_classification_map.

conversion routes. The decision on what conversion route is chosen is based on the relative cost differences between the routes, which depend on the capital costs, operational costs, feedstock costs and other costs (policy costs or benefits from electricity generation) per GJ-HVC.

2.1.4. Pulp & paper industry

The pulp & paper industry has a cradle-to-cradle value chain representation in the IMAGE model framework. Three pulping feedstocks (mechanical pulp, chemical pulp and recovered paper) and three paper product groups (writing, paper and paperboard and other) are represented (drawing from [48]). Total demand is correlated to the income per capita via a logistic growth formulation although some decoupling is imposed over time. The model focuses on the thermal energy demand associated with the pulping and paper industry, fulfilling this demand with four different heat technologies (CHP, secondary heat, heat pump, boiler). Heat demand technologies can be fuelled by multiple energy carriers, such as coal, oil, natural gas, biomass (which can be black liquor based), electricity and hydrogen. The conventional CHP option is available with and without carbon capture and storage (based on Onarheim et al. [49]). Thermal heat capacities are allocated based on the relative costs differences among the options. Feedback loops are included for both the black liquor residue coming out of the Kraft pulping process and paper waste being recovered and reused via a simple recycling process. Recycled paper feeds back into the production process based on a scenario-dependent recycle rate and the amount of used paper available for recycling.

2.2. Scenarios

In this study, we assess four archetypical decarbonisation scenarios for the industry sector that have been developed in the European H2020 REINVENT project [36] (see Table 1). The scenarios have been developed by mapping multiple innovation case studies [21], insights from stakeholder workshops [5,33,34,56] and systems-engineering research [70] to two axes creating a quadrant with four distinct narratives. The first axis identifies where a change is introduced in the industrial value chain, such as upstream (affecting production processes) or downstream (changing a product or service). The second axis focuses on whether an industrial strategy can reduce or avoid emissions [36]. Subsequently, we have translated the collected techno-economic and socio-technical information into quantitative inputs that can be read by the IMAGE integrated assessment model. In the following sections, we will elaborate more on how these narratives are interpreted per industry. An overview of the quantitative parameterisation is provided in Table B-1 in the supplementary information.

Table 1
Overview of the archetypical decarbonisation scenarios.

Scenario	Description
Technological Replacement (TechReplace)	Focusing on scaling up new innovative production methods. This narrative explores the availability of these (readiness and implementation timescales) and the potentials or trade-offs of focusing on new methods
Process Efficiency (ProcEff)	Focusing on optimising today's systems, either by assuming the availability of Best Available Technologies (BAT) or establishing further efficiency improvements via economies of scale. This scenario explores the effects of better upstream supply chain performance
Demand Management (DemandMan)	Focusing on managing consumption and waste. The scenario explores the effects of reduced consumption and downstream supply chain management
Circular Economy (CircEco)	Focusing on closing the material and carbon loops in the system. This scenario explores the effects of improved recycling and the utilization of waste streams
Total (Total)	Combining all strategies described above[a].

[a] A combined scenario leads to some narrative inconsistencies between *TechReplace* and *ProcEff*, and *CircEco* and *DemandMan* due to several conflicting configurations of measures. As a result it cannot fully depict a combined effect of all measures. This scenario is therefore only intended to be an illustrative example.

2.2.1. Technology replacement

The *Technology Replacement (TechReplace)* narrative describes a pathway in which heavy industry pursues alternative production routes. For the iron & steel sector, the scenario includes a narrative in which the sector moves away from using metallurgical coal as a reducing agent and focuses on processes that reduce iron using hydrogen (H-DRI) (drawing from Vogl et al. [70]) or electrolysis (electrowinning) (drawing from EC [14]) instead. The adoption of these innovative production routes is forced into the IMAGE model framework from respectively 2030 and 2040 onwards. For the clinker & cement sector, the electric dry rotary lime kiln is promoted, alongside the adoption of carbon capture and storage installations. For the chemical industry, a narrative is modelled in which the industry moves away from fossil-based feedstock uses and starts focusing on using renewable or alternative feedstocks for olefin production instead, such as biomass and recycled CO_2. CO_2 recycling (or carbon looping, utilizing end-of-pipe CO_2 emissions as a feedstock into a methanol-to-olefin production route) has been forced into the IMAGE modelling framework and is assumed to become available from 2040 onwards (drawing from Schneider et al. [56]). No explicit alternative production route is modelled for the pulp & paper industry. However, all fossil-fuelled heating technologies are excluded as an investment option from 2025 onwards as a strategy to lower emissions.

2.2.2. Processefficiency

The *Process Efficiency (ProcEff)* narrative describes a pathway in which existing capital stock is replaced by the best available technologies. For the iron & steel sector, the narrative entails that new capital investments in standard BF/BOF are banned from 2020 onwards to focus more on the adoption of more efficient blast furnaces (drawing from van den Berg et al. [63]) or direct reduction processes (DRI) in conjunction with carbon capture and storage (CCS) facilities. For the clinker & cement sector, the narrative only allows new capital investments into the more energy-efficient clinker & cement production technologies. This is represented by an option that includes improved process and fuel control systems, more efficient pre-heaters and pre-calciners and improved cooling/heating recovery systems. For the chemical industry, a narrative is followed in which fossil-fuelled processes are replaced with electric alternatives (such as an electric cracker) from 2025 onwards. This process is completed within the assumed average lifetime of a steam cracker (25 years) [36]. To represent the narrative in the pulp & paper sector, all non-CHP boilers are excluded as an option for investments to stimulate energy efficiency in this scenario. Additionally, electrification of heat supply is promoted.

2.2.3. Demand management

The *Demand Management (DemandMan)* narrative describes a pathway in which societal actors are empowered to change the industrial system by changing their total demand for (primary) materials. This can be achieved by adopting social innovations (e.g. extending the lifetime) or by seeking out efficiency improvements (material efficiency). To represent this, we gradually lower the primary demand for steel and cement by 1.5% and 1% per year (drawing from Material Economics [41]). Secondly, as the iron & steel sector is the only sector with an explicit representation of material stocks, we have extended the lifetimes of all steel applications by 30%. The chemical industry and the pulp & paper sector also include assumptions on increased recycling to lower primary material demand, e.g. by increasing the recycling rate to the assumed practical limits as described in Material Economics [41]. The pulp & paper sector also includes a redistribution of demand, replacing 20% printing paper demand for 20% more packaging paper.

As a trend of decoupling is already visible in total paper demand, this narratives also includes a 10% additional reduction by 2050 compared to the baseline estimate.

2.2.4. Circular economy

The *Circular Economy (CircEco)* narrative describes a pathway in which the focus shifts from primarily primary production routes to closed production cycles. For all the basic materials, scrap recovery and recycling rates are therefore increased using the assumptions in Material Economics [41] as the upper range of achievable rates. In the absence of any material feedback loops for the cement sector in the IMAGE model, the overall cement demand has been reduced to reflect the spirit of the narrative for this sector. Circularity has also been more thoroughly embedded into the chemical sector by forcing CO_2 recycling into the IMAGE modelling framework, representing the use of internal CO_2 emissions as a feedstock for the methanol-to-olefins conversion route. Additionally, process integration is forced into the IMAGE modelling framework by linking the pulping industry to the chemical industry (allowing the use of black liquor as a feedstock for plastics production (drawing from Schneider et al. [56]).

2.3. Implementation in IMAGE

The storylines have been implemented into the IMAGE modelling framework (see Annex B in the supplementary information for an overview). Additional to the formulated industry-specific narratives, we also implement a universal carbon price that drives both the industry and the rest of the economy to make choices in favour of decarbonisation. The carbon price is a simple method used in the IMAGE model framework to change the relative price levels of energy carriers across the modelled system. We apply a stylized[2] carbon price trajectory that ramps up to $USD\$_{2020}$ 1100 / tCO_2 from 2020 to 2040 and flattens out to a threshold value of $USD\$_{2020}$ 1500 / tCO_2 (see Fig. 1A). This trajectory reflects a carbon price level that allows the modelled system to meet the Paris climate agreement (see Fig. 1B). To maintain comparability between scenarios, we apply the same price trajectory across all scenarios and focus on the impact thereof on the energy system. The combination of both the carbon price (applied to all economic sectors to a similar degree) and the industry-specific narratives (additional incentives specific to the industry sector) leads to significantly different pathways for the global energy system. In the next section, we focus specifically on the implications for the industry sector, although broader energy system changes apply (see Annex C in the supplementary information for further details on the broader energy system implications).

3. Results

3.1. Industry in a global net-zero carbon emissions context

The concept of net-zero carbon emissions implies a complex sum of all anthropogenic emission sources and removals by sinks. Ambitions that apply to a global context, like the Paris climate agreement, trickle down to varying degrees across the various regional and sub-sectoral systems and in time. This section assesses the implications of a global net-zero CO_2 emissions ambition while looking at the regional and industrial implications. We distinguish between the regional difference in direct (scope 1) and the combination of direct and indirect emissions (scope 1+2) in 2050 and the temporal differences in reaching (net) zero emissions in the (sub)sector(s) itself.

As shown in Fig. 2A, meeting a net-zero CO_2 emissions goal on a global and economy-wide level leads to different effects in the industry sector and the underlying industrial subsectors. In general, the sector as a whole is projected to maintain a level of annual residual direct emissions by 2050 (blue bars, showing a range of 9-18% on a global scale, with regional differences between 0%-45%). Only the North American industry sector is projected to align with the global economy in meeting its zero emissions mark. Latin America, Africa and Asia follow suit in subsequent decades. The bulk of EU and the Rest of World projections show to never reach zero carbon emissions within the time horizon of the IMAGE model. If broader energy system changes are taken into account, and particular net-negative indirect emissions (red bars in Fig. 2A), we find that the IMAGE model renders the industry sector carbon neutral more early on than considered for the global economy under the global net-zero emissions mark (see Fig. 2B) (with an exception for the EU and the Rest of World regions (2050s)). The scenario narratives show to impact the change in indirect emissions (larger range) more significantly than the direct emissions by 2050.

Similar results are observed on an industrial subsectoral level. Substantial residual emissions are projected to remain across the industrial subsectors by the time that a global economy-wide net-zero ambition is met (up to ~70% in e.g. the iron & steel sector (Africa) or chemical sector (Latin America)). For the bulk of scenarios, the IMAGE model even projects that zero direct emissions are not feasible over the time horizon of the model for most regions and scenario narratives. Given the more early-on carbon neutrality indication for the iron & steel, clinker & cement and chemical sectors (see Fig. 2B), it also implies a high reliance on compensation mechanisms over time, which are most notable for the iron & steel sectors in Africa and Latin America (see also Figure C-3 in the SI). Moreover, in the Rest of the World region, it is more challenging to decarbonise the basic industries, as (net) zero emissions are more frequently reached later in time than in the other world regions or not at all (as found for the clinker & cement and iron & steel sector). EU and Asia are also regions for which the IMAGE model projects a slower mitigation response than other world regions. The pulp & paper sector, on the other hand, reaches (net)zero emissions as early as 2030 for nearly all regions and scenario narratives.

3.2. Industrial decarbonisation strategies

As each of the modelled industrial subsectors have a unique formulation in the IMAGE modelling framework, we decompose their strategic movements over time and space in more detail. To test the models' choice and flexibility, we specifically look into how the model chooses between (1) energy or carbon efficiency, (2) fuel switching options and (3) specific technology choices.

3.2.1. Focus on energy or carbon efficiency

By framing the decarbonisation strategies in terms of their energy and carbon intensity per unit of production (see Fig. 3), we see again that the decarbonisation strategy is strongly industry and region dependent. However, on a narrative level, we see that the model responses are broadly similar, therefore creating clustered responses. Most of the 'travel' on the plot occurs in the period 2020-2050 (solid lines), with generally only marginal changes post-2050 (dotted lines).

Towards the 2050 global net-zero CO_2 emissions objective (solid lines), we see that the clinker & cement sector universally increases its energy demand per unit of production across every major region (doubling even in Africa), with carbon intensity gradually decreasing more successfully for the Americas and Africa. Similarly, but in the opposite direction, the chemical sector shows a clear universal focus on energy efficiency, with Asia and Western countries facing initial challenges. The iron & steel sector shows an initial energy efficiency pathway. However, it seems to blend out into a response that either entails energy intensity increases (EU and Africa) or declines (other major regions) with both routes leading to a successful decarbonisation of the sector under the *TechReplace* scenario (as indicated in Fig. 2). The

[2] Adapted from an existing cost-optimal SSP2 1.5°C scenario and adjusted to start from a 2020 base year. The carbon price should be seen as a generic policy pressure (representing a wide range of policy instruments) that can lead to systemic behavioural change towards decarbonisation.

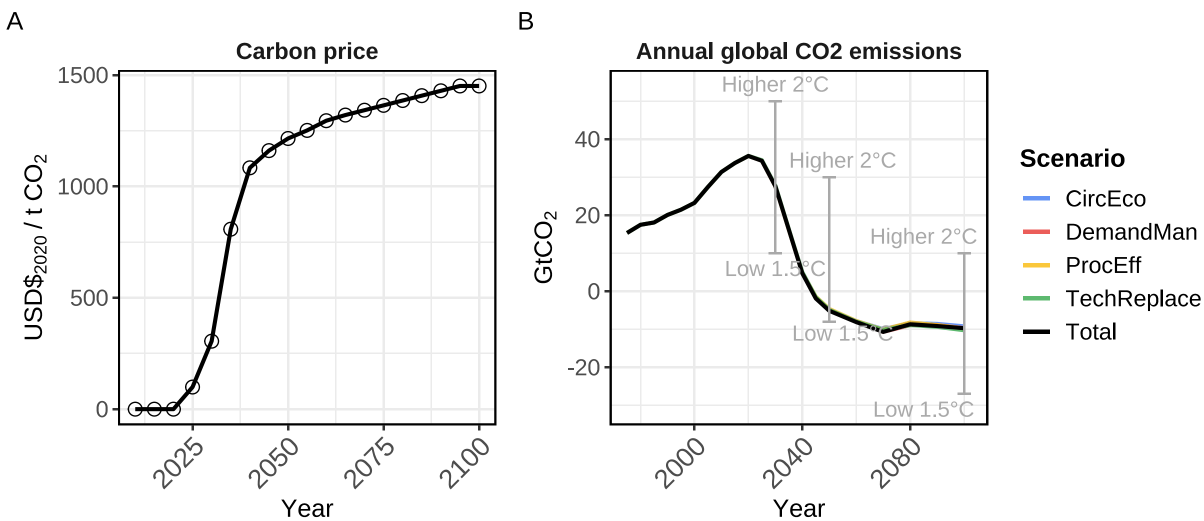

Fig. 1. Implemented global settings: global carbon price (A) and the global annual CO_2 emissions for the energy system (B). To test the scenarios with their alignment to the Paris Agreement, we plot the pathways together with the estimated energy system emission bandwidths as published in Rogelj et al. [53] (Fig. 2.6, p. 117).

pulp & paper sector shows a combination of increasing (mainly Africa) and declining energy intensities, with a universal decline in carbon intensity across all the regions (albeit to a more limited extent for Asia and the Rest of World region).

The year 2050 shows to be a clear inflection point for several sectoral decarbonisation strategies. Particularly the clinker & cement sector (with the exception of Africa), but also the iron & steel sector (only in Africa), show a sudden shift from an increasing to decreasing energy intensity in the second half of the 21th century. Other responses indicate that sectors that focused hard on negative carbon intensities pre-2050 are curving back towards a zero carbon intensity once a global net-zero emissions objective is met (dotted lines). Some general further declines in energy intensity per tonne product are achieved post-2050 (with Africa being the exception in the clinker & cement and the pulp & paper sector as a result of rapid new capacity building with a higher energy use), which seem to move towards an energetic optimum for some sectors (see also Figure F-1 in the supplementary information).

3.2.2. *Focus on fuel switching*

To further unpack the decarbonisation strategies per industrial subsector in the IMAGE modelling framework, we look at the specific choices for energy carriers over time (see Fig. 4). We find that the clinker & cement and chemical sectors have a relatively similar starting point (using predominantly fossil fuels) but different strategic patterns over time. Although both sectors initially appear to move towards biofuel uses, it can be observed from Fig. 4 that the clinker & cement sector returns to fossil fuel uses even before global net-zero emissions are achieved (with an exception found for the Rest of the World region). The chemical sector adopts a more linear path, combining fossil fuel use (at least 40% of total energy demand) with alternative fuels and electricity.

The iron & steel and pulp & paper sectors show to be more regionally differentiated regarding their starting position for the overall energy mix. Under a global net-zero CO_2 emissions objective, the iron & steel sector mostly switches fossil fuels for biofuels and electricity. *TechReplace* is the only pathway that leads to zero direct emissions in the iron & steel sector (see also Fig. 2). It shows a different response with more radical short-term fuel switching to biomass and greater electrification towards 2100. The pulp & paper sector, on the other hand, shows a relatively linear pathway towards a blend of electricity and biofuels, with developed regions having a greater preference for clean fuels. At the same time, Asia leans more towards electricity use.

3.2.3. *Focus on technology choices*

In order to draw lessons of which industrial decarbonisation strategies are considered the most effective in decarbonising the industrial (sub)system, we decompose the technology pathways that present a fully decarbonised industrial subsystem. To maintain comparability between the various industry sectors, we present their decarbonisation strategies by grouping the specific production technologies per sector into five standardized categories, which are (see table D-1 in the supplementary information for a detailed breakdown):

1 **Fossil-based production capacity**: all production capacity that exists today and that predominately utilizes fossil fuels without abating energy or process emissions;
2 **CC(U)S**: All technologies that include carbon capture and storage or innovative new technologies that can recycle CO_2;
3 **Energy innovations**: all technologies that consist of adopting innovations related to the more efficient use of fuels, or using fuels with a lower carbon content than hydrocarbons, for driving the production processes (e.g. fuel switching, energy and thermal efficiency improvements);
4 **Process innovations**: all technologies that consist of adopting innovations that improve the carbon efficiency in the represented capital stock or feedstock uses (e.g. direct electrification, feedstock substitution);
5 **Material innovations**: all technologies that consist of adopting innovations relating to the use of materials (e.g. consumption, material efficiency, end-of-life measures).

We present the decarbonisation strategies side-by-side (see Fig. 5), while recognizing the regional, temporal and industrial differences as presented in earlier sections.

As shown in Fig. 5, the IMAGE projections show that zero emissions in the clinker & cement sector are mostly achieved if the sector shifts away from unabated fossil-fuel based production capacity to carbon capture and storage. If combined with biomass-fired lime kilns (creating negative emissions), some unabated production capacity (either standard or efficient lime kilns) can remain in operation without compromising the zero emissions status in this sector. In other cases the fossil-based capital stock is projected to be phased-out around the 2050 time window.

The chemical sector is projected to reach zero emissions via process innovations, CC(U)S and material innovation. Two pathways are visible,

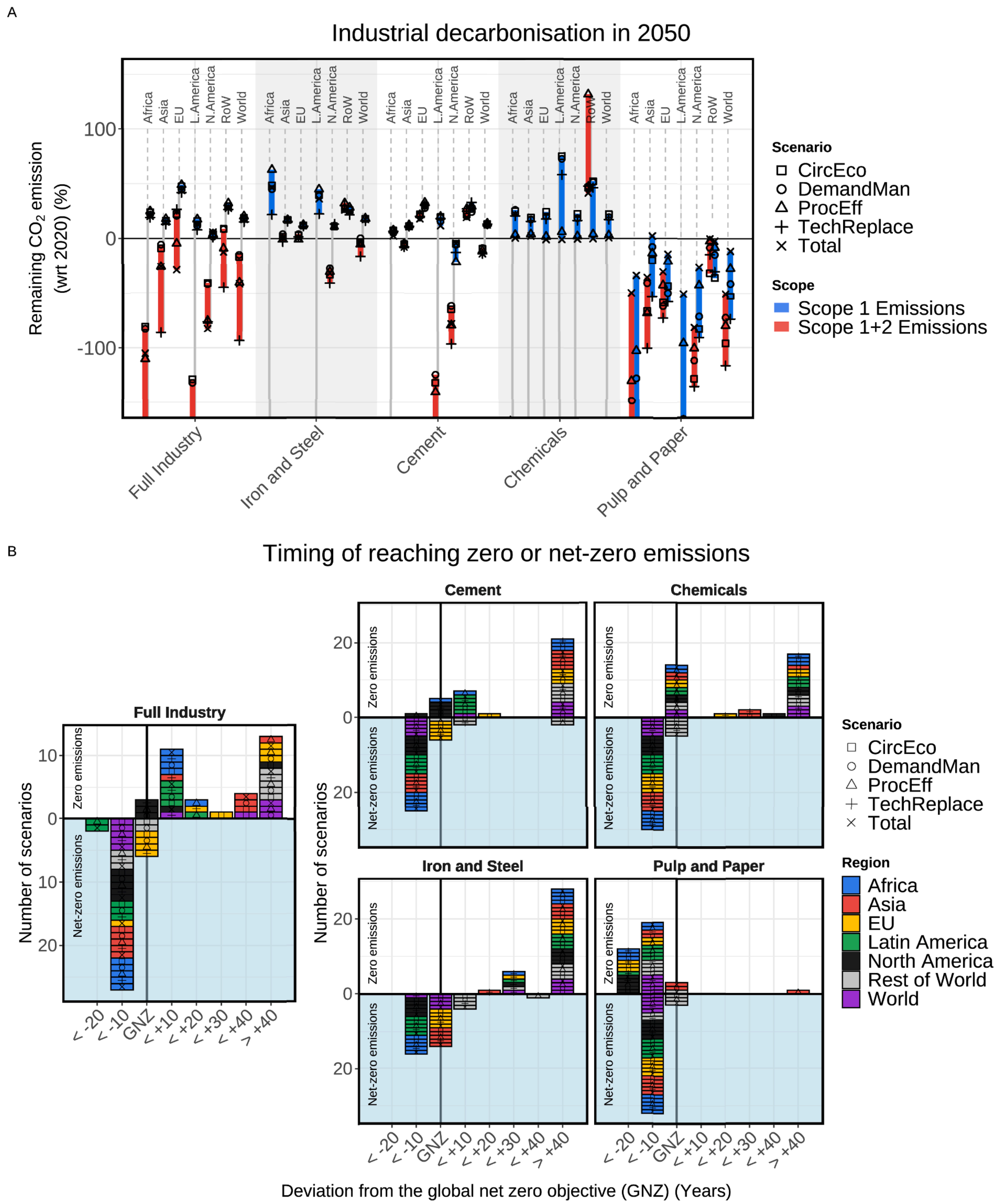

Fig. 2. Overview of (A) responses per industry and region for remaining direct emissions (scope 1 emissions) and net emissions (scope 1+2 emissions) in 2050. The dotted line represents the drift from 2020 values; the solid line represents the drift among the zero and net-zero interpretations. Subplot (B) represents the difference in timing of when the industry sector itself is projected to reach the zero (direct, scope 1) emissions and net-zero emissions (direct+indirect, or scope 1+2) mark compared to the global net zero objective (GNZ). EU: European Union, L. America: Latin America, N.America: North America, RoW: Rest of World (Russia and Central Asia)

either through decarbonising the cracking processes (e.g. the electric cracker in *ProcEff* with an assumed closed material system) which allow the continued use of fossil feedstock, or through capturing the internal carbon emissions of the production routes and utilizing this waste stream as a feedstock (*TechReplace* and *CircEco*). Both require a strong narrative that enforces a shift from traditional production routes to the inclusion of carbon or material looping. The regional responses are broadly similar in the IMAGE modelling framework, although a greater focus on bio-based plastics production is projected for Europe than any other represented region.

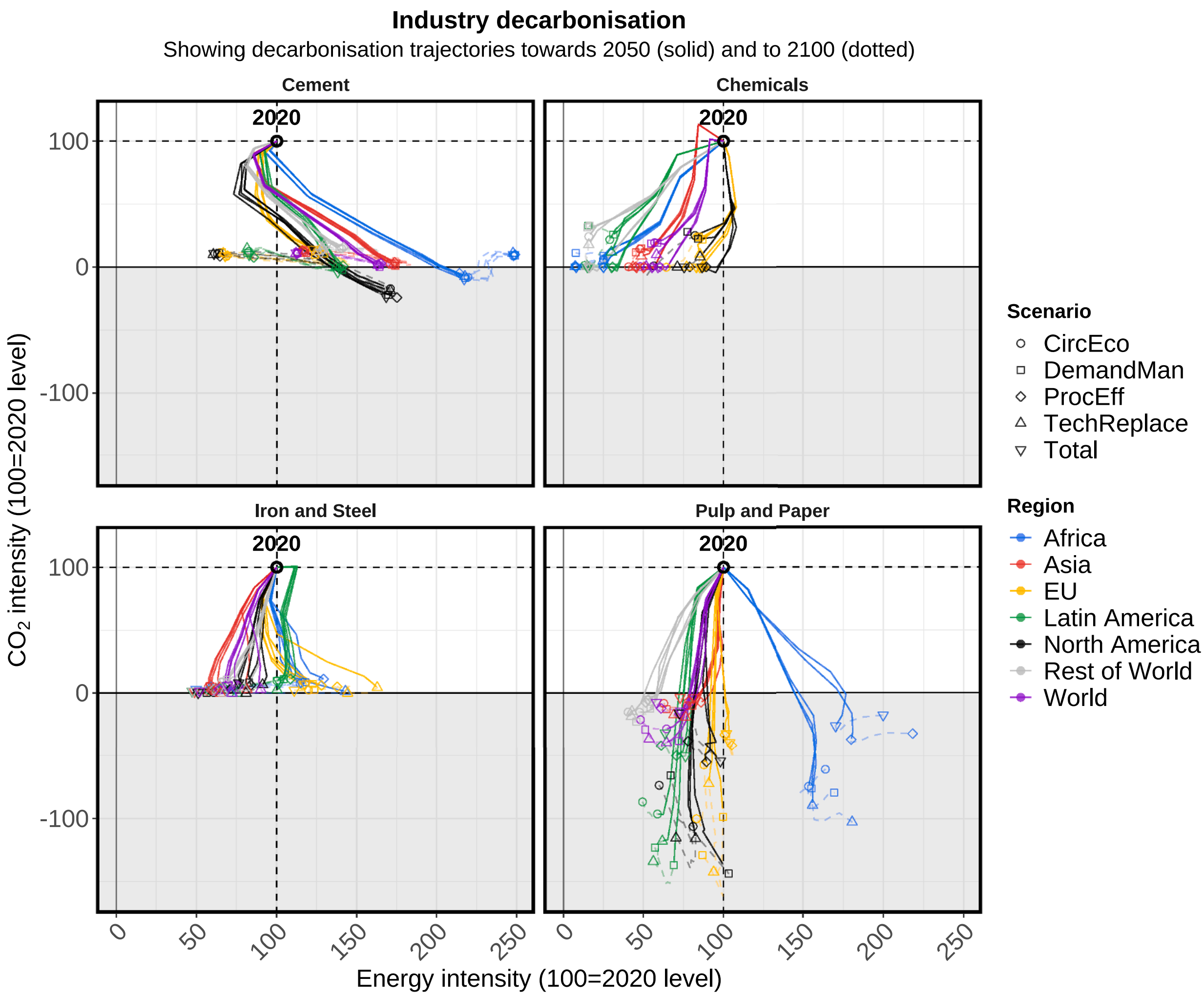

Fig. 3. Overview of decarbonisation trajectories for major regions and over the time horizon of the IMAGE model (2020 to 2100). Solid lines are used for trajectories towards 2050. Dotted lines are used to indicate the 2050-2100 period. For a breakdown per scenario, see Table F-2 in the SI.

The iron & steel sector is characterised in the IMAGE model as a sector that sustains a level of residual emissions over time unless a strong normative scenario is implemented (as shown in Fig. 2). The only pathway that has led to a full decarbonisation of the iron & steel sector (see Fig. 5) is one that focusses on 100% (in)direct electrification via process innovations (40%-80% of total capacity comprising of both hydrogen or electrochemical steelmaking) and material innovations (20%-60% of total capacity that focuses on the electric arc furnace, showing an increase in secondary steel use in all regions, except Africa). However, despite an assumed global market entrance and uptake of zero-carbon steel making technologies[3] as early as 2030 (see Table B1 in the SI) it takes the IMAGE model another 30 years to fully phase-out remaining unabated capital stock (such as the blast furnace) and reach zero direct emissions in *TechReplace*. A side effect of a growing use of the electric arc furnace is the significant energy intensity cut as demonstrated for Asia and the Rest of World region also depicted in Fig. 3. The response of the iron & steel sector is broadly similar across the various represented regions in the IMAGE modelling framework.

For the pulp & paper sector, a large share of the technological capital stock across the world is already utilizing renewable energy carriers in 2020 (considered under energy innovation, with the exception of Africa). The decarbonisation pathways imply a strengthening of the use of renewable energy carriers in combination with CC(U)S. The more use of bio-fuelled heating capacity, the lower the dependency on CC(U)S.

4. Discussion

In this study we have decomposed the decarbonisation strategies for the industrial subsectors that can be represented by the IMAGE integrated assessment model. The IMAGE integrated assessment model underpins that net-zero emission pathways for industry should outpace or broadly align with the global economy-wide net-zero timeline. The timing of reaching carbon neutrality in the industry sector mostly hinges on the expected availability of bioenergy and/or CCS to industry (most prominent for the pulp & paper and cement sectors) and of decarbonised electricity supply (for (in)direct electrification of production processes in the iron & steel and chemical sector). Particularly the latter is found to be key to rendering the carbon-intensive industries carbon neutral on time, especially if indirect emission removals area ssumed. Without these indirect emission removals, we find that this study reproduces much of the conclusions already addressed in literature on 'residual emissions' and 'hard-to-abate sectors' [16,39,46]. Given the increasing interest in developing zero-carbon solutions for various carbon-intensive industries and regions in the real world [15,19,44,62], and the uncertainties revolving around reaching the required levels of net-negative

[3] H-DRI, although widely anticipated as the technology to deliver 'green' steel [20,70], is mostly interpreted as 'blue' steel in the IMAGE model (using 'blue' hydrogen, produced through steam methane reforming and partial oxidation of oil, as this has more favourable techno-economic conditions than 'green' hydrogen) (see Annex C of the supplementary information).

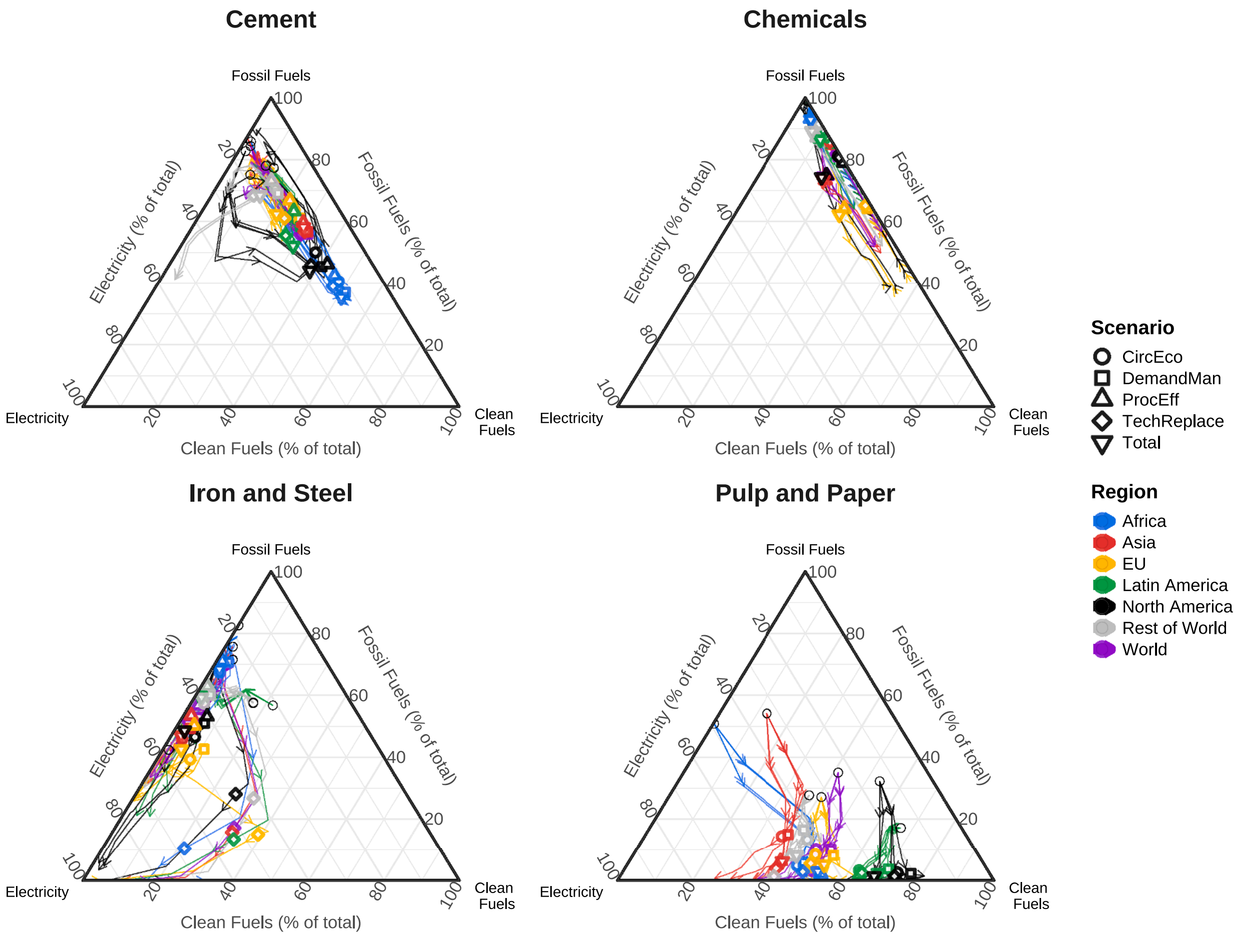

Fig. 4. Ternary diagrams of the energy mix per industry and decarbonisation narrative over the 2020-2100 period. The category ‚Clean fuels' represents the sum of hydrogen, biofuel, secondary heat and feedstock recycling. Circles indicate the starting position in 2020. Arrow tips are placed on the year 2025, 2035, 2050 and 2100 to indicate direction.

emissions in the electricity supply sector, it leads to question how future-proof these modelled dynamics and the resulting depictions of change are in the context of the upcoming 'race to zero' [62].

Earlier studies have argued that the 'hard-to-abate' narrative in global models is a result of various limitations in integrated assessment modelling, such as an overall energy supply-side and up-stream focus [50,52], a lack of explicit representation or oversimplifications of the industrial value chains (and the options to decarbonise them) [66] and some ingrained or imposed conservatism in the model parameterisation and structure [28,68,69]. In fact, the depictions could be considered more extrapolations of todays' systems under pressure than those of the future [69]. To challenge the underlying mechanisms in the 'hard-to-abate' narrative, and to scope out a broader range of 'solution space' for industry within a net-zero context, a more anticipatory focus is needed on upcoming policy, technology and societal developments [42, 52]. Generally, this implies, amongst others, a more explicit view on the scaling potentials of zero-carbon production processes, zero-carbon materials or fuels and representations of carbon management, demand management and asset management processes [10,45,52,72].

In light of a more anticipatory focus, the trend in the IMAGE model has been to pursue more innovative, granular, dynamic and integrated 'up-stream' (Kermeli et al. [32], this paper) and 'down-stream' [12,13, 31,40,43] representations of various industrial value chains. However, given the vast range of possibilities and the plethora of specificities per industrial value chain, these efforts have so far mostly focused on ad-hoc (e.g. imposed, without feedbacks), single-issue (e.g. only energy focused) or local (e.g. only a part of the value chain) improvements. As a result, there is still a long way to go before all relevant aspects to assess the position and role of industry in a global net-zero CO_2 emissions context are included. Other topics of study that have been explored in the broader field are the needed early capital retirements [37,60], shifted or reduced consumption [26]), relocation of production systems [20] and trade-offs within the broader economy-wide mitigation strategy [29].

As integrated assessment models are frequently used tools to explore the 'solution space' towards a certain policy goal, it is of the essence for these models to capture the dynamics of the prospective worlds that they try to represent. Given the existing limitations in current available tools and data [47,73], the wide variety of interpretations in modelling [16] and net-zero end-points [58] and the absence of a focused collaborative platform [30], it underscores that there is still a major analytical gap left that needs to be overcome. Further research on the role of industry in a net-zero world is thus recommended within and beyond the integrated assessment modelling community [17,28,52].

5. Conclusions

In this study we have decomposed the industrial decarbonisation strategies that are adopted by the IMAGE integrated assessment model under a global 2050 net-zero carbon emissions context. We have analysed the responses of the IMAGE modelling framework to four polar decarbonisation narratives for industry and across six different regions to test the effectiveness and robustness of the decarbonisation strategies over time. The following lessons can be drawn from this exercise:

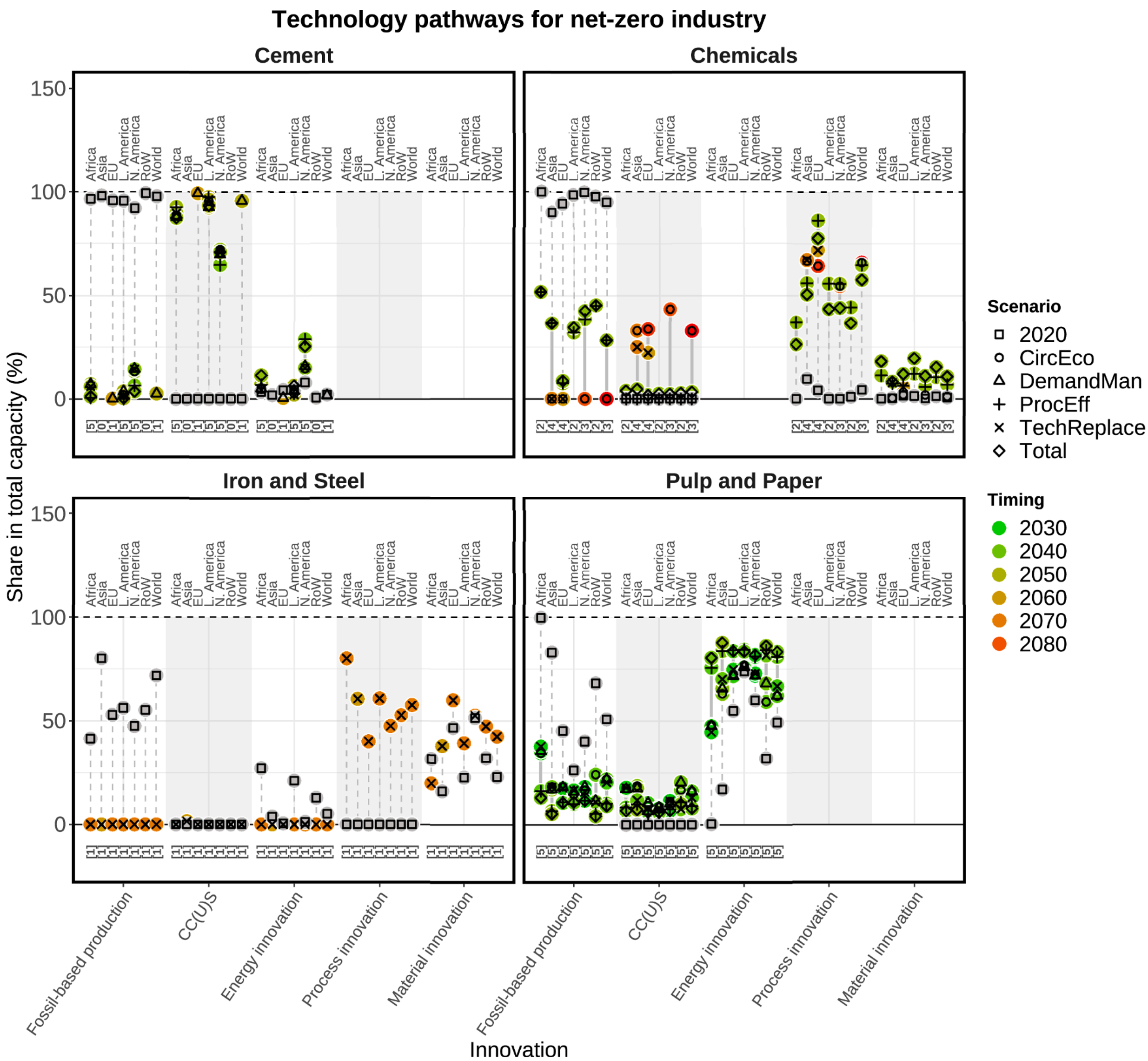

Fig. 5. Overview of the share of a specific innovation in total capacity under a zero emissions industry context. Grey coloured indicators represent the base values (2020). Dotted line represents the drift from the 2020 value, the solid line the drift among the mitigation scenarios. The number in brackets represents the number of included pathways that lead to zero-carbon industry.

The IMAGE integrated assessment model underpins that net-zero emission pathways for industry should outpace or broadly align with the global economy-wide net-zero timeline. The bulk of industrial decarbonisation pathways analysed in this study indicate that residual emissions remain over the full time horizon of the IMAGE model (with the pulp & paper sector as an exception). This outcome can still be considered consistent with a global 2050 net-zero ambition if negative indirect emissions, achieved by radically decarbonising the power and energy conversion sectors, can compensate for the residual emissions left in the industry sector. If negative indirect emissions are accounted for, it is observed that the IMAGE model can render many of the carbon-intensive industries 'net-zero' as early as 2040. Zero direct emission pathways for industry are found to be theoretically available for the pulp & paper sector within the 2050 timeline. Other sectors can achieve zero carbon emissions under very specific narratives, but likely outside of the 2050 timeline. Particularly iron & steel and the chemical sector are projected as hard-to-abate sectors in the IMAGE integrated assessment model, given their need of very specific narratives (based on electrification) or long or lacking time frame towards zero and net-zero CO_2 emissions themselves.

The decarbonisation patterns in the IMAGE model are industry and regionally specific, though they remain broadly similar under different strategic considerations. The different strategic considerations (narratives) did not substantially change the models' response to decarbonisation in the industry sector. For example, electrification is presented a core strategy in the iron & steel sector under all decarbonisation pathways, whereas zero-carbon fuels and feedstocks are at the core of the clinker & cement, chemicals and pulp & paper sector (combined with and without CC(U)S). We find that particularly the chemical and iron & steel sector benefit from a strong technology-oriented decarbonisation narrative. Narratives about demand management benefitted the clinker & cement sector.

Increased research efforts are needed to overcome several representational limitations of industry in computational models. In this study, we have addressed industrial decarbonisation from a whole value chain and integrated system dynamic perspective to provide insights into industry's role in a global net-zero CO_2 emissions context. We found that the IMAGE modelling framework faces challenges in portraying zero and alternative pathways towards the full decarbonisation of the industry sector. As our choice and use of research methods and frameworks have a determining role in how we look at a problem or frame the considerable solution space, it would help if more focused and diversified research is done on the subject of industrial decarbonisation.

Declaration of Competing Interest

No conflicts of interest are considered.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.egycc.2021.100051.

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