Assessing the cumulative impacts of sectoral decarbonisation pathways for heavy industry

Deliverable 4.10

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2020-07-31

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1 Introduction

The European Green Deal (EC, 2019) has set a net zero emissions target for 2050. Depending on the activities in other sectors, this means that also industry emissions will have to be reduced substantially – and possibly reach a zero emission target in 2050 as well. There are different possible routes to decarbonise the industry sector. They all have different consequences and are associated with different interests of actors involved. In this deliverable we assess four different kinds of archetypal innovation pathways (Lane, 2019). The long-term implications of these narratives are assessed by using the global integrated assessment model IMAGE. IMAGE can depict the effects of different response strategies for industry in a broader systems perspective.

This deliverable builds on earlier work performed within the European H2020 REINVENT project. In addition to deliverable D3.7 (Lane, 2019), we also built upon the work performed under deliverable D4.3 (bottom-up modelling) (Schneider et al., 2020), deliverables D4.4-D4.9 (co-creation workshops with stakeholders) (Aan den Toorn and Tziva, 2019; Bauer and Nilsson, 2019; Knoop et al., 2019a; Knoop et al., 2019b; van Sluisveld et al., 2019; van Veelen and Bulkeley, 2019). This deliverable feeds into deliverable D5.3 (broader impacts) (Hof et al., 2020) in WP5, describing the interactions of industry with the rest of the economy.

This report starts by introducing the material and methods used in this deliverable (Chapter 2), the results (Chapter 3), discussion (Chapter 4) and closes with final conclusions (Chapter 5).

2 Methods

We apply the Integrated Model to Assess the Global Environment (IMAGE) modelling framework in order to explore the potential and implications of industrial change (Stehfest et al., 2014). A description of the basic functionalities of IMAGE and its industry representations has been provided in Deliverable D4.2 (see Van Sluisveld et al. (2018) for further detail). In this publication we will describe in more detail the process of translating qualitative narratives of decarbonisation pathways (as presented in (Lane, 2019)) to model-based scenarios that can be assessed by the IMAGE modelling framework.

2.1 Scenario narratives

2.1.1 Narrative framework

The qualitative narratives as published in (Lane, 2019) have been developed using a quadrant diagram, allowing the studied innovations in REINVENT to be mapped across two linked axes (see Figure 1):

- **The Process-Product/Service axis**: defining where in the value chain the responsibility of decarbonisation is most likely taken, such as at the front (production process) or at the back (consumer) of the value chain.

- **The Avoidance-Reduction axis**: Defining the nature of the decarbonisation measure, framing it around reduction (mitigation) or avoidance (prevention).

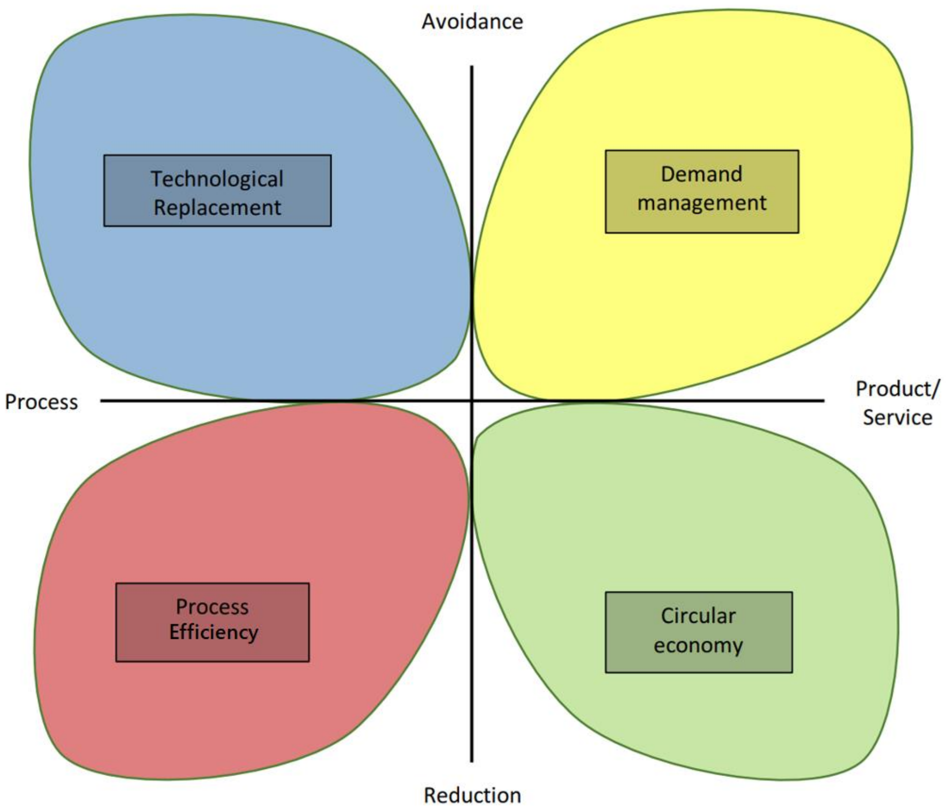

Figure 1: Conceptual overview of the qualitative decarbonisation narratives
Adapted and reprinted from Lane (2019)

2.1.2 Narratives

The innovation-decarbonisation typological space provided the outlines of four archetypical (normative) scenarios that are studied in further detail:

– **Technological Replacement (TechReplace)**: The focus for *Technological Replacement* is 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)**: The focus of *Process Efficiency* is on optimising today's systems, either by assuming the availability of Best Available Technologies (BAT) or through establishing further efficiency improvements via economies of scale. This scenario explores the effects of better upstream supply chain performance;

- **Demand Management (DemandMan)**: The focus of *Demand Management* is on managing consumption and wastage. The scenario explores the effects of reduced consumption and downstream supply chain management;

- **Circular Economy (CircEco):** The focus *of Circular Economy* is on closing the material and carbon loops in the system. This scenario explores the effects of improved recycling and the utilization of waste streams.

While the focus may differ between the scenarios, they will also share many of the same characteristics. The innovations presented in the REINVENT Decarbonisation Innovations Database (D2.1) (Hansen et al., 2019), sectoral reports (D2.2-D2.6) and Innovation biographies (D2.7) undertaken within WP2, as well as the in-depth case studies (D3.3) undertaken within WP3 and further desk-based research provide the detailed input used to draft the narratives and provide input to the IMAGE model.

2.2 Scenario implementation

To translate the qualitative narratives from Lane (2019) into implementable model-based scenarios for the IMAGE modelling framework, several core elements of the narratives have been defined. For this the narratives were simplified into the following key elements:

- Key innovation(s) being described;
- Timing of adoption or completion of the transformation;
- Trade-offs that can stimulate or hamper adoption.

2.2.1 Quantitative implementation

The default model parameterisation is based on (1) available empirical data on the costs and energy use of technological change and (2) expert estimation in the absence of actual data. By formulating new narratives for the future, a different response by the IMAGE model framework has to be enforced. In order to 'code' the new narratives into model-readable parameters, the right (context) variables have to be located in the model and new values or trajectories to the *Default* parameterisation have to be set (leading to a new model response). These (context) variables are specific to the model; hence implementation is a result of the modeller making an interpretation of the narrative, as well as the availability of (context) parameters in the model that can possibly be changed.

2.2.2 Qualitative implementation

Under circumstances that a narrative cannot be codified into exact quantitative material, e.g. when only a direction rather than an exact quantification is indicated, several interventions in a default response are available to the IMAGE modelling framework that can shape a narrative (see Figure 2 for a conceptual overview):

- **Cap growth** (plot A): Imposing a threshold of allowable expansion. This intervention can be used in two ways: it can impose a limitation of one development to allow space on the playing field for a competing development. Alternatively, socio-economic correlations between material demand and income levels can also be decoupled through capping to a certain threshold or floor value. Secondly, the threshold can be increased, e.g. to represent technological development that leads to a higher maximum recycling rate;

- **Stop adoption** (plot B): Removing the option from the decision tree and offering a new playing field to the remaining alternatives to cost-optimally decide on a new equilibrium. For example, fossil fuel driven technologies that do not have an option to retrofit carbon capture and storage facilities can be banned from a certain time onwards. The option can be removed directly or allowed to be gradually phase out;

- **Force alternative** (plot C): One can promote the adoption of a desired option by influencing the market dynamics; Forcing an alternative option implies, for example, giving a certain pre-emptive advantage (or preference) to a technology during a period of time when it experiences a disadvantage. This can be done by adding a premium or discount (reflective of a subsidy programme) to the economic drivers of the desired option;

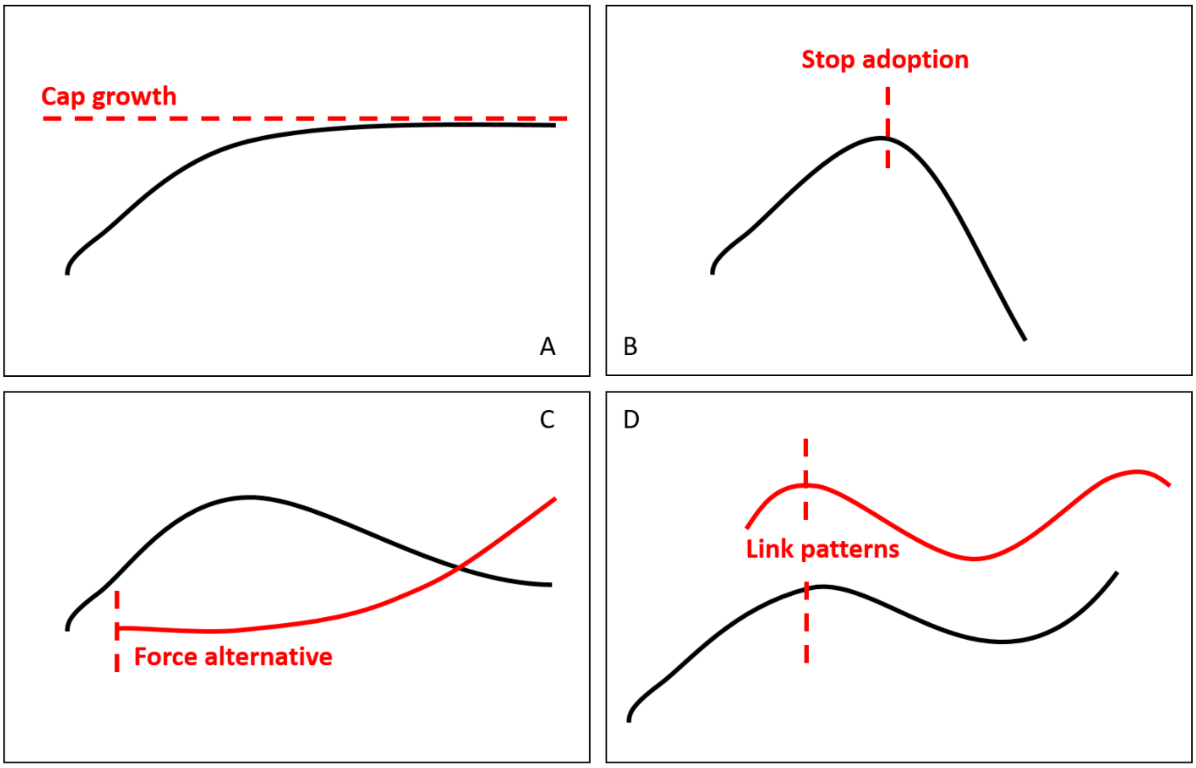

Figure 2: Conceptual overview of applicable model interventions for qualitative inputs

- **Link patterns** (plot D): By introducing new dependencies to the model one can change the model response dynamics. An example of this is by applying a convergence of the economic parameters of option A to the economic parameters of option B (reflective of R&D policy). This option is particularly attractive in the case of highly innovative technologies with little information about the expected economies of scale over time. By linking patterns, it prevents the need for the modeller to make explicit assumptions about the height of premiums or the developments of the costs. It creates an immediate levelized playing field with equally attractive options available to the decision module.

2.3 Model parameterisation

2.3.1 Global policy assumptions

To represent a decarbonisation strategy, we implement a similar and rapidly increasing carbon price in all narratives. The carbon price reflects a policy pressure with *the highest urgency* in mind to decarbonise the human system (see Figure 3-A). The trajectory over time follows a cubic root shape, reflecting a political transition phase that ramps up to a near threshold by 2040. From 2040 the carbon price levels off to a threshold of USD$ 4000 / tC – a level in which the maximal decarbonisation potential of the IMAGE modelling framework is achieved. The carbon price affects only the carbon content in fuel use and not the carbon embedded in products. The carbon price and the decarbonisation strategies in the archetypical narratives are implemented on a global scale, indicating that all countries follow a similar trajectory as Europe.

Although this scenario implies that about 8% to 15% of residual greenhouse gas (GHG) emissions remain in Western Europe mid-century (reaching net-zero around 2060), it leads to a net-zero *global* greenhouse gas emissions pathway in 2050. The narratives indicate alignment with the global Paris Climate Agreement goal of limiting global warming below 2°C by the end of the century (IPCC, 2018), reaching total cumulative greenhouse gas emissions between 650-1050 $GtCO_2$-eq by 2100 (See Figure 3 B-C).

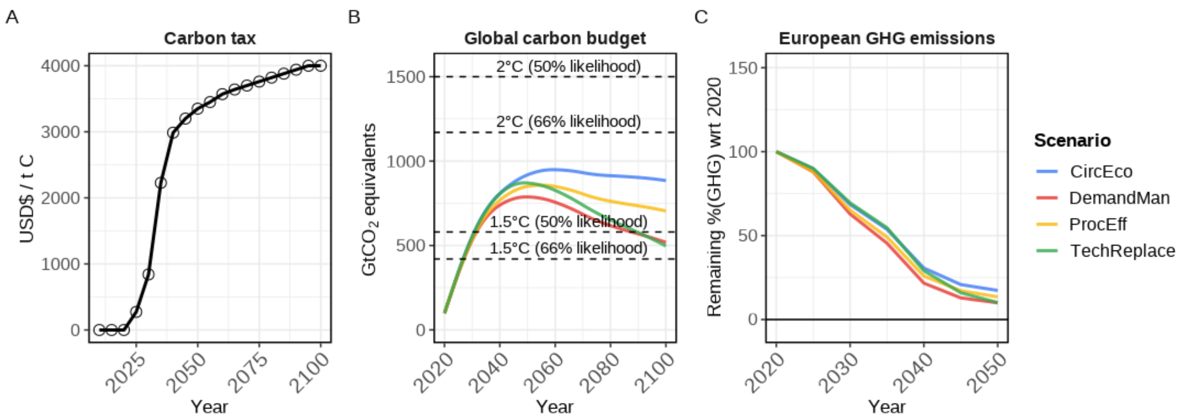

Figure 3 - Implemented global settings: global carbon tax (A), global carbon budget (B) and remaining European economy GHG emissions since 2020 (C)

2.3.2 Sectoral policy assumptions

In this section we describe the areas of decarbonisation that are included in the IMAGE model on default and the interventions that have been introduced through the archetypical narratives. To make the strategies comparable across the sectors, we distinguish the various decarbonisation measures in three different categories: decarbonisation achieved through (1) energy innovation, (2) process innovation and (3) material innovation.

1. **Energy innovations**: all innovations related to the more efficient use of fuels, or using fuels with a lower carbon content, for driving the production processes (e.g. fuel switching, energy and thermal efficiency improvements);
2. **Process innovations**: all innovations relating to the efficiency or carbon removal capacity of the represented capital stock or feedstock uses in the production process (e.g. technology innovations, feedstock substitution or CC(U)S);
3. **Material innovations**: all innovations relating to the use of materials (e.g. consumption, material efficiency, end-of-life measures).

The following sections will first describe the representation of the industry in the IMAGE model as-is, before describing the new model parameterisation per archetypical scenario. Each section concludes with an overview table. A full overview is provided in Figure 4.

2.3.2.1 Steel industry

The steel industry representation in the IMAGE model framework includes a cradle-to-cradle value chain for iron to steel production and use (Van Sluisveld et al., 2018). In order to supply steel to society, the model can dispatch 14 different existing and innovative steel production routes. Decision-making for production capacity is based on the current stock in place and the costs of implementing a new production route (accounting for CAPEX, OPEX and policy costs). Steel demand is allocated over four different product groups (e.g. buildings, machinery, cars and packaging) (Van Ruijven et al., 2016). Lifetimes for production routes are fixed (30 years) without the option for early retirement or retrofitting (despite a depreciation time of +/- 7 years that allows smooth transitioning into a new option). 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.

2.3.2.1.1 Technology Replacement

The *Technology Replacement (TechReplace)* narrative describes a pathway in which low-carbon alternative production routes for steel are rapidly ramped up, with a focus on the innovative “hydrogen reduced iron” (H-DRI) (drawing from Vogl et al. (2018)) and the “electrochemically reduced iron” (electrowinning) (drawing from EC (2016)) production routes. The adoption of these innovative routes is forced into the IMAGE model framework from 2040 onwards.

2.3.2.1.2 Process Efficiency

The *Process Efficiency (ProcEff)* narrative describes a pathway in which existing capital stock is replaced by the best available technologies in a cost-effective way. As a result, 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 Vuuren et al. (2018)) or direct reduction processes (DRI) in conjunction with carbon capture and storage (CCS) facilities.

2.3.2.1.3 Demand Management

The *Demand Management (DemandMan)* narrative describes a pathway in which societal actors are empowered to drive industrial transformation through changing the total demand for steel, either via the adoption of social innovations (e.g. via extending the use of steel applications) or seeking out efficiency improvements in steel applications (material efficiency).

2.3.2.1.4 Circular Economy

The *Circular Economy (CircEco)* narrative describes a pathway in which the focus is on less primary steel production and more circular use of steel scrap. Scrap recovery and recycling rates are therefore increased in the IMAGE modelling framework, using the assumptions in Material Economics (2018) as the upper range of achievable rates. Although some efficiency improvement is included for the electric arc furnace, no innovations are adopted in the model that can lead to systemic closed-loop recycling. The pathway therefore assumes an ever-present need for primary feedstock.

An overview of the implemented scenario assumptions is provided in Table 1.

Table 1: Scenario assumptions for deep mitigation in the steel industry

All measures are assumed to be adopted from 2020 onwards unless otherwise stated (adoption year indicated within parentheses). The alphabetic letter between brackets refers to the applicable model interventions in Figure 2. The cell colour indicates to what extent the decarbonisation strategy is dynamically represented in the IMAGE model.

Legend Not available / Not pursued (grey) Available and included on default (blue) Narrative driven stimulance (green)		**Default**	**TechReplace**	**ProcEff**	**DemandMan**	**CircEco**
Energy	Indirect electrification				Promoted [C]	Promoted [C]
	Energy efficiency			Phase-out standard BF/BOF [B]		
Material	Material efficiency			0.995	1.57% p.a[2] [A]	
	Lifetime extension	Buildings: 70 (±30) years Machinery: 20 (±7) Years Cars: 15 (±5) years Packaging: 5 (±3) years			+30%[2] [A]	
	Recycling	70%				85%[2] [A]
Process	Technological innovation		Force H-DRI / Electrowinning[1] (2040) [C]			
	CCS					

1. Lane (2019)

2. Material Economics (2018)

2.3.2.2 Cement industry

The cement industry representation in the IMAGE modelling framework includes a cradle-to-gate value chain of clinker and cement production. Clinker and cement production is represented via a stylised representation of a facility operating a dry rotary lime kiln. The sector has the option to dispatch 4 different kinds of rotary lime kilns (differing in efficiency and retrofitting carbon capture and storage). Decision making for production capacity is based on the current stock in place and the costs of implementing a new production route (accounting for CAPEX, OPEX and policy costs) (Van Ruijven et al., 2016). Lifetimes for production routes are fixed (25 years) without the option for early retirement or retrofitting, no feedback loops are modelled to fields of application (e.g. buildings and construction). 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 (Kermeli et al., 2019).

Given how the focus of the REINVENT project has been on other sectors than the cement sector, no archetypical narratives have been developed for this sector. To remain consistent in developing a transition pathway for industry, several developments in this sector have been promoted.

2.3.2.2.1 Technology Replacement

The *Technology Replacement (TechReplace)* narrative describes a pathway in which an electric dry rotary lime kiln is promoted, alongside further adoption of carbon capture and storage installations.

2.3.2.2.2 Process Efficiency

The *Process Efficiency (ProcEff)* narrative describes a pathway in which only the more energy efficient cement production technologies are available for new capital investments. These efficient dry feed rotary kilns include: improved process and fuel control systems, more efficient pre-heaters and pre-calciners and improved cooling/heating recovery systems.

2.3.2.2.3 Demand Management

The *Demand Management (DemandMan)* narrative describes a pathway in which society reduces their demand for cement, either through social innovations or through reducing overconsumption (e.g. by not excessively reinforcing constructions) (drawing from Material Economics (2018)).

2.3.2.2.4 Circular Economy

The *Circular Economy (CircEco)* narrative describes a pathway in which society reduces their demand for cement by recycling concrete after use. Due to a lack of a representation of this feedback loop in the IMAGE modelling framework, a total reduction of (primary) material demand has been assumed.

An overview of the implemented scenario assumptions is provided in Table 2.

Table 2: Scenario assumptions for deep mitigation in the cement industry

All measures are assumed to be adopted from 2020 onwards unless otherwise stated (adoption year indicated within parentheses). The alphabetic letter between brackets refers to the applicable model interventions in Figure 2. The cell colour indicates to what extent the decarbonisation strategy is dynamically represented in the IMAGE model.

Legend
- Grey: Not available / Not pursued
- Blue: Available and included on default
- Green: Narrative driven stimulance

		Default	TechReplace	ProcEff	DemandMan	CircEco
Energy	Indirect electrification	(blue)	Promoted [C] (green)	(blue)	(blue)	(blue)
	Energy efficiency	(blue)	(blue)	Phase –out standard kiln [B] (green)	(blue)	(blue)
Material	Material consumption	(grey)	(grey)	(grey)	-20% (2050)[A] (green)	(grey)
	Material efficiency	(blue)	(blue)	(blue)	(blue)	-10% (2050) [A] (green)
Process	CCS	(blue)	(blue)	(blue)	(blue)	(blue)

2.3.2.3 *Chemical industry*

The IMAGE modelling framework includes a cradle-to-gate value chain representation of the chemical industry (Daioglou et al., 2014), with a simplistic representation of recycling. For the implementation of the narratives this study has focused solely on the "high value chemical" (HVC) subsection of the model (reflecting olefins such as ethylene and propylene). The model includes a representation of 9 production routes for (bio) ethylene of (bio) propylene; which either include traditional routes utilizing fossil-based feedstocks (assuming gas or naphtha cracking) or innovative routes such as coal-to-olefins or utilizing non-fossil feedstocks (such as biobased feedstocks or CO_2). Production capacities are allocated based on the relative costs differences among the production routes, including estimations of the capital costs, operational costs, feedstock costs and other costs (policy costs or benefits from electricity generation) per GJ-HVC. The processes are assumed to be continuous, without explicit representation of capital stock or consumer products. Future demand of olefins is based on an extrapolation of the regional historic relationship between production and GDP.

2.3.2.3.1 Technology Replacement

The *Technology Replacement (TechReplace)* narrative describes a pathway in which the chemical industry moves away from pyrolysis cracking processes and fossil-based feedstocks. Instead, the chemical industry adopts more innovative production processes by utilizing waste streams from other industries as a new feedstock for plastics production. Carbon looping has been forced into the IMAGE modelling framework, representing the use of internal CO_2 emissions as a feedstock for the methanol-to-olefin production route (CO2MTO). This production route is assumed to become available from 2040 onwards (drawing from Schneider et al. (2020)).

2.3.2.3.2 Process Efficiency

The *Process Efficiency (ProcEff)* narrative describes a pathway in which the chemical industry follows a cost-effective pathway under restricted fossil fuel use from the year 2025 onwards. All fossil fuel driven processes have been substituted by electric alternatives (such as electric cracking, electrification)

(Lane, 2019). Due to limited representation in the model and data availability on innovative production technologies, a linear transformation is assumed substituting ethane driven processes for electric ones over a period of 25 years (within the assumed average lifetime of a steam cracker).

2.3.2.3.3 Demand Management

The *Demand Management (DemandMan)* narrative describes a pathway in which demand for primary feedstocks is lowered via enhanced mechanical recycling and reuse schemes (drawing from Material Economics (2018)).

2.3.2.3.4 Circular Economy

The *Circular Economy (CircEco)* narrative describes a pathway in which total demand for primary feedstocks is lowered via an enhanced recycling scheme (for both mechanical and chemical recycling, drawing from (Material Economics, 2018)). Carbon looping has also been forced into the IMAGE modelling framework, representing the use of internal CO_2 emissions as a feedstock for methanol production that can be used for HVC (CO2MTO). 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 (BLG2MTO)) (drawing from Schneider et al. (2020)).

An overview of the implemented scenario assumptions is provided in Table 3.

Table 3: Scenario assumptions for deep mitigation in the chemical industry

All measures are assumed to be adopted from 2020 onwards unless otherwise stated (adoption year indicated within parentheses). The alphabetic letter between brackets refers to the applicable model interventions in Figure 2. The cell colour indicates to what extent the decarbonisation strategy is dynamically represented in the IMAGE model.

Legend: Not available / Not pursued (grey); Available and included on default (blue); Narrative driven stimulance (green)		Default	TechReplace	ProcEff	DemandMan	CircEco
Energy	Direct electrification			Forcing E-cracker[2] (2025) [C]		
Material	Recycling	MR[1]: 30% CR[1]: 20%			70%[3] (MR[1]: 33% CR[1]: 37%) [A]	70%[3] (MR[1]: 33% CR[1]: 37%) [A]
Process	Technological innovation	-		Forcing E-cracker[2] (2025) [C]		
	Feedstock substitution	Biobased				
	CCU	-	Forcing CO2MTO[2] (2040) [D]			Forcing CO2MTO[2] (2040) and BLG2MTO[2] (2040) [D]

1. MR: Mechanical Recycling, CR: Chemical Recycling
2. Lane (2019); Schneider et al. (2020)
3. Material Economics (2018).

2.3.2.4 Pulp and paper industry

The IMAGE modelling framework includes a cradle-to-gate value chain representation of the pulping and paper industry, with a simple representation of fibre recycling. 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 (OECD/FAO, 2017)). Total demand is correlated to income per capita via a logistic growth formulation, applying a time factor to represent decoupling. The model focuses on the thermal energy demand that is associated in both the pulping and paper industry, fulfilling this demand with 4 different heat technologies (CHP, the use of secondary heat, heat pump, boiler). Heat demand technologies can be fuelled by multiple secondary energy carriers, such as coal, oil, natural gas, biomass (which can be black liquor based), electricity and hydrogen). The convectional CHP option is available with and without CCS. The model decides how to invest based on the total production cost per technology, including CAPEX and OPEX. Technologies with lower total production cost get a higher share of production and technologies with higher total production cost get a lower share.

Feedback loops are included for both the black liquor residue coming out of the Kraft pulping process being used as energy inputs 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.

2.3.2.4.1 Technology Replacement

In the *Technology Replacement (TechReplace)* narrative all technologies driven by fossil fuels are excluded as an investment option from 2025 onwards as a strategy to lower emissions.

2.3.2.4.2 Process Efficiency

The *Process Efficiency (ProcEff)* scenario excludes non-CHP boilers as an option for investments in order to stimulate energy efficiency. Also, the use of electricity is promoted for heat production.

2.3.2.4.3 Demand Management

The *Demand Management (DemandMan)* narrative includes measures to lower the demand for (virgin) paper and change the distribution of demand (20% less printing paper and 20% more packaging paper). Absolute consumption per capita has also been restricted by implementing a floor value of 200 kg/cap per year. Furthermore, material efficiency and recycling rates are increased.

2.3.2.4.4 Circular Economy

In the circular economy scenario, recycling rates are increased in order to represent a transition towards a circular economy.

An overview of the implemented scenario assumptions is provided in Table 4: Scenario assumptions for deep mitigation in the pulp & paper industry.

Table 4: Scenario assumptions for deep mitigation in the pulp & paper industry

All measures are assumed to be adopted from 2020 onwards unless otherwise stated (adoption year indicated within parentheses). The alphabetic letter between brackets refers to the applicable model interventions in Figure 2. The cell colour indicates to what extent the decarbonisation strategy is dynamically represented in the IMAGE model.

Legend Grey: Not available / Not pursued Blue: Available and included on default Green: Narrative driven stimulance		**Default**	**TechReplace**	**ProcEff**	**DemandMan**	**CircEco**
Energy	Indirect electrification			Promoted [C]		
	Energy efficiency			Non-CHP boilers ban [B]		
	Fuel switching		Fossil ban [B]			
Material	Material consumption reduction	Decoupling -1% p.a.			-10% (2050)	
	Material efficiency				-2% p.a.	
	Recycling	66.5% (2050)			69% (2050)	74% (2050)
Process	Technological innovation					
	CCS					

1. Lane (2019)

2. Material Economics (2018)

2.3.2.5 Food industry

The IMAGE modelling framework includes a cradle-to-grave value chain representation of the food system, ranging from a detailed representation of food demand (Bijl et al., 2017), the agricultural systems (Stehfest et al., 2009b) to food processing (Van Sluisveld et al., 2018).

The food demand representation includes consumption patterns driven by population and income levels. It applies the Engels law, which states that households with lower incomes generally spend a larger share of their income on food (Engel, 1857). The IMAGE modelling framework represents demand for 46 food categories as adopted in the food balance sheets of the FAO (http://www.fao.org/economic/ess/fbs/en/), which link to the functions of food for end-users (energy, protein, flavour, vitamins) (Bijl et al., 2017).

The agricultural system in IMAGE contains a detailed cropland and livestock representation. The merit order for cropland uses is decided upon by assessing the available crop yield potential (Müller et al., 2016), accessibility (Nelson, 2008), population density (Goldewijk et al., 2010) and the terrain slope indexes (Fischer et al., 2002). Subsequently, livestock production in both intensive and extensive systems is represented by taking into account large variations between regions in feed composition, feed efficiency, genetic animal productivity and age at slaughter (Doelman et al., 2018; Stehfest et al., 2014)

The food processing sector is mostly concerned with the thermal energy demand needed to process food. Thermal energy demand is split up in low temperature heat demand (below 100 degrees Celsius) and high temperature heat demand (above 100 degrees Celsius) based on (Naegler et al., 2015). Thermal demand can be fulfilled with 4 different heat technologies (CHP, the use of secondary heat,

heat pump, boiler) which can be fuelled by multiple secondary energy carriers depending on the technology: coal, oil, natural gas, biomass, electricity and hydrogen). Some technologies, like heat pumps, are only available for low temperature heat supply.

2.3.2.5.1 Technology Replacement

The *Technology Replacement (TechReplace)* narrative describes a pathway in which artificial meat is developed and accepted by society, starting in 2035. This study assumes an 80% replacement of meat and eggs (but not fish and seafood) by artificial meat by 2050. Artificial meat is grown directly from corn and small amounts of soy (drawing from (Mattick et al., 2015; Sung et al., 2004), indicating the use of 1.197 kg of corn and 0.008 kg of soybeans per kg meat (or 2.4 kcal corn and 0.02 kcal soy per kcal meat)). This study also assumes an 80% substitutability of dairy products with plant-based alternatives, using 0.35kg of oats and 0.04 kg of rapeseed to replace 1 kg of dairy milk (Oatly, 2018; Sethi et al., 2016).

Technological innovation is also implemented on the agricultural level – assuming emission reductions in line with (Smith et al., 2016): maximum CH_4 reductions are set to: Enteric fermentation in ruminants: 73%, Sewage: 95%, Landfills: 100%, Animal waste / manure: 100%. And maximum N_2O reductions to: Fertilizer use: 80%, Animal waste / manure: 75%.

2.3.2.5.2 Process Efficiency

The *Process Efficiency (ProcEff)* narrative describes a detail pathway of agricultural intensification, including optimistic assumptions on the development of crop yields and the efficiency of livestock production systems. Maximum crop yields per region are derived from Doelman et al. (2018) and are implemented to reach 70% in 2050. Livestock systems are assumed to globally convergence to the most efficient systems for up to 80% in 2100. The efficiency gains are mostly possible due to large-scale technological improvements such as improved feed digestibility and animal health, as well as higher animal productivity from genetic improvement and reduced age at slaughter (Herrero et al., 2016). Because traditional livestock systems are assumed to continue to exists, no full convergence is assumed (Bouwman et al., 2005). Food waste in storage and distribution systems is reduced by 5% per year starting in 2020 (reaching 86% in 2050) (for details, see (Bijl et al., 2017)).

2.3.2.5.3 Demand Management

The *Demand Management (DemandMan)* narrative describes a detailed pathway that includes dietary change and food waste reduction. For dietary change, a quick adoption of a healthier diet (the so-called Willett diet) is forced into the model between 2020 and 2050, with low levels of meat consumption: 10.4 kcal/cap/day of cattle, 16.0 of pork, 32.3 of eggs, 33.2 of poultry and 13.0 kcal/cap/day of fish and seafood (Willett, 2005). The reduced consumption of meat proteins is compensated by increasing pulses/oil crops (mostly soy) and adjusting staples/luxuries to keep the total calories as in the default scenario. Earlier implementations of this scenario have been described in detail (Bijl et al., 2017; Stehfest et al., 2009a). Food waste as fraction of total demand is reduced in households (10% less avoidable waste per year starting in 2020, reaching 98% reduction in 2050) (for details, see (Bijl et al., 2017)).

2.3.2.5.4 Circular Economy

The conceptualization of circularity in terms of the food industry have been considered unavailable for the IMAGE modelling framework. *CircEco* therefor assumed the standard techno-economic drivers of change.

An overview of the implemented scenario assumptions is provided in Table 5.

Table 5: Scenario assumptions for deep mitigation in the food industry

All measures are assumed to be adopted from 2020 onwards unless otherwise stated (adoption year indicated within parentheses). The alphabetic letter between brackets refers to the applicable model interventions in Figure 2. The cell colour indicates to what extent the decarbonisation strategy is dynamically represented in the IMAGE model.

Legend: Not available / Not pursued (grey); Available and included on default (blue); Narrative driven stimulance (green)		Default	TechReplace	ProcEff	DemandMan	CircEco
Energy	Indirect electrification	(blue)	(blue)	(blue)	(blue)	(blue)
	Energy efficiency	(blue)	(blue)	(blue)	(blue)	(blue)
	Fuel switching	(blue)	(blue)	(blue)	(blue)	(blue)
Material	Material consumption	(grey)	(grey)	(grey)	Willet Diet (2020):[2] 10.4 kcal/cap/day cattle, 16.0 kcal/cap/day of pork, 32.3 kcal/cap/day of eggs, 33.2 kcal/cap/day of poultry 13.0 kcal/cap/day of fish and seafood [A]	(grey)
	Material efficiency	(blue)	(blue)	-5% p.a. less waste through value chain[2] [A]	-10% p.a. food waste reduction [A]	(blue)
Process	Technological innovation	(blue)	Livestock efficiency[2]: CH4 emission reductions: -73% Enteric fermentation in ruminants, -95% Sewage, -100% Landfills, - 100% Animal waste / manure. N_2O emission reductions: -80% Fertilizer use, -75% Animal waste / manure. [A]	Livestock efficiency[2] (-60% emissions in 2050) [A]	(blue)	(blue)
	Feedstock substitution	(grey)	-80% of animal replaced with plant[1,2] (2035) [C]	(grey)	(grey)	(grey)

1. Lane (2019)
2. Stehfest et al. (2009b); van Vuuren et al. (2018)

2.3.3 Total overview

The archetypical narratives established a new configuration of the IMAGE modelling framework (see Figure 4). Although differences exist across the industry representations, much of the mitigation potential already included in the IMAGE model is focused on energy use. As underscored in Figure 4, greater diversity in decarbonisation strategies can be embedded through the adoption of archetypical narratives (particularly for material and process related innovations).

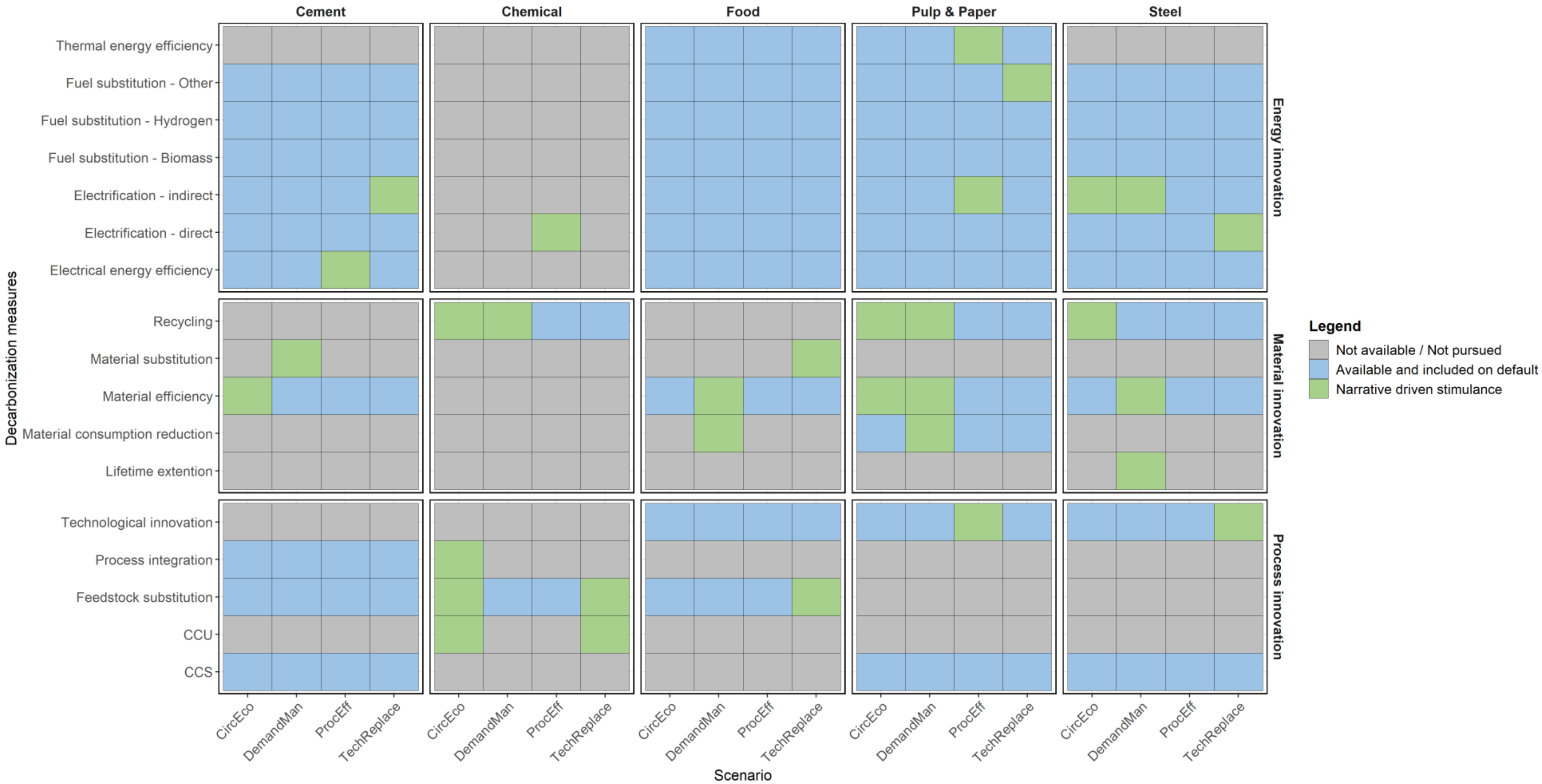

Figure 4 - Overview of decarbonisation measures represented in the IMAGE model and narrative driven changes

3 Results

This chapter presents the results of the IMAGE integrated assessment framework. In this deliverable only the effects for the industry sector are described, further economy-wide effects are discussed in deliverable D5.3.

3.1 Carbon emissions and goal achievement

The total impact of the archetypical narratives on industry decarbonisation can be viewed in Figure 5. As also underscored in Figure 6, only a few industries are able to contribute to the European net-zero objective for 2050, respectively the chemical industry for a single scenario and the pulp and paper industry. Regardless of the narrative assumed, the cement sector is projected to reduce its total direct CO_2 emissions by ~90% under stringent decarbonisation policies in 2050. Similar reduction rates are projected for the chemical sector for the technology-oriented narrative (*TechReplace*), while the consumer-oriented narratives (*DemandMan* and *CircEco*) achieve lower emission reductions by 2050 (stagnating at about 80%). Replacing the existing capital for electric alternatives allows the chemical sector to decarbonise their process related emissions before 2050. The iron and steel industry shows a solid 7% emission reduction rate per annum for each archetypical narrative, reaching about 90% emission reductions by 2050. The food processing sector shows the least CO_2 emission reductions of all scrutinised industries, maintaining a similar level of carbon emissions until 2040. From that point onwards, the pace of the food sector transition will parallel with the one of the power sector.

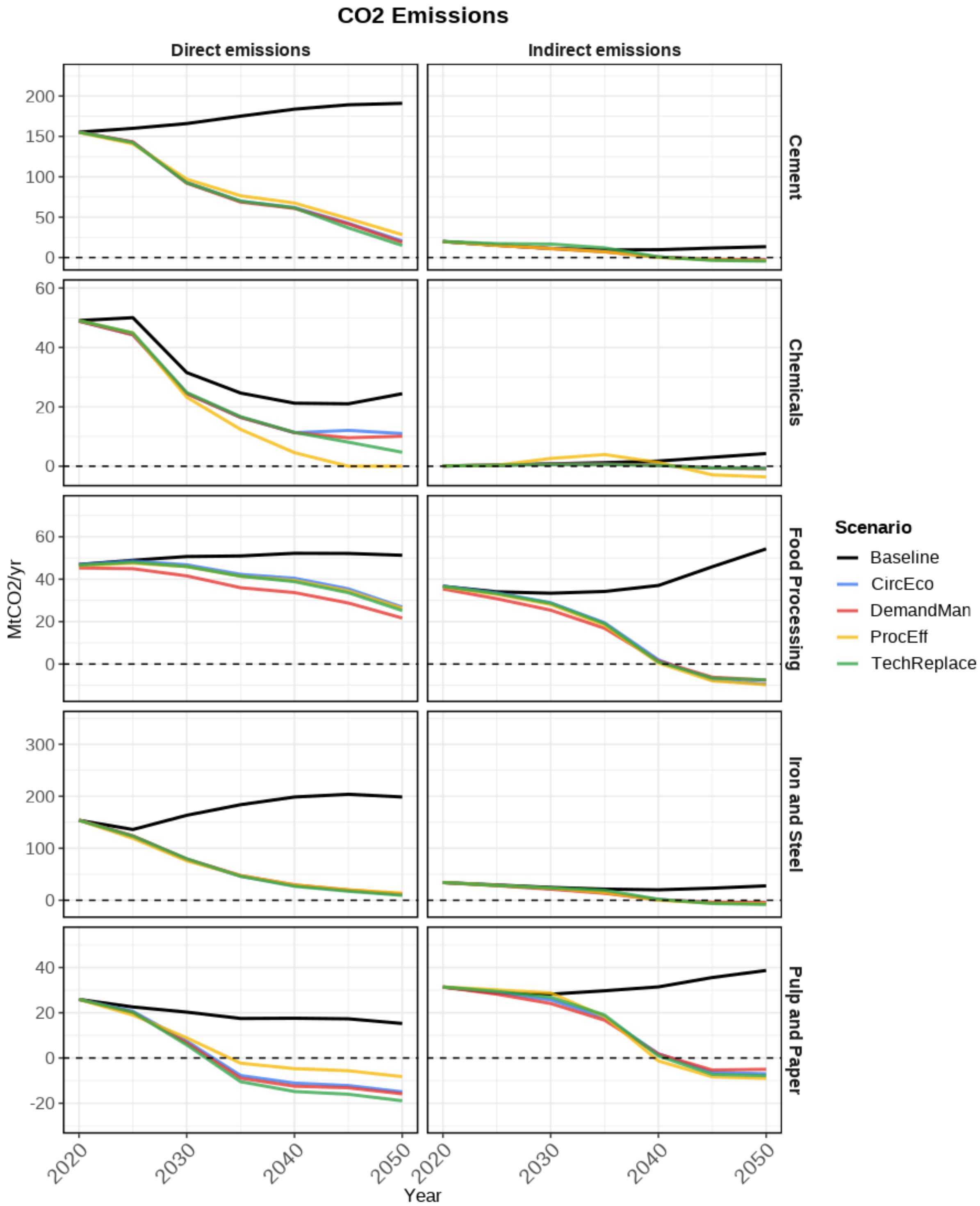

Figure 5 - Overview of total direct and indirect CO_2 emissions per year for each sector and archetypical narrative.

Direct emissions are emissions generated from on-site fuel burning and process related emissions. Indirect emissions are emissions from electricity, secondary heat and hydrogen production not produced on-site.

The results show that narrative-driven assumptions can influence the timing of when net zero CO_2 emissions are achieved by the material processing industries (see Figure 6). The technology-oriented narratives (*TechReplace* and *ProcEff*) show to reach that objective more early on that those that are more consumer oriented (*DemandMan* and *CircEco*), particularly for the chemical industry. Narratives that do not include a clear focus on carbon removal techniques or technologies show to maintain some residual emissions towards the end of the time horizon in the IMAGE model (indicated by “>2100” in Figure 6), preventing the industry from reaching net zero (as seen for Food processing and the iron and steel industry).

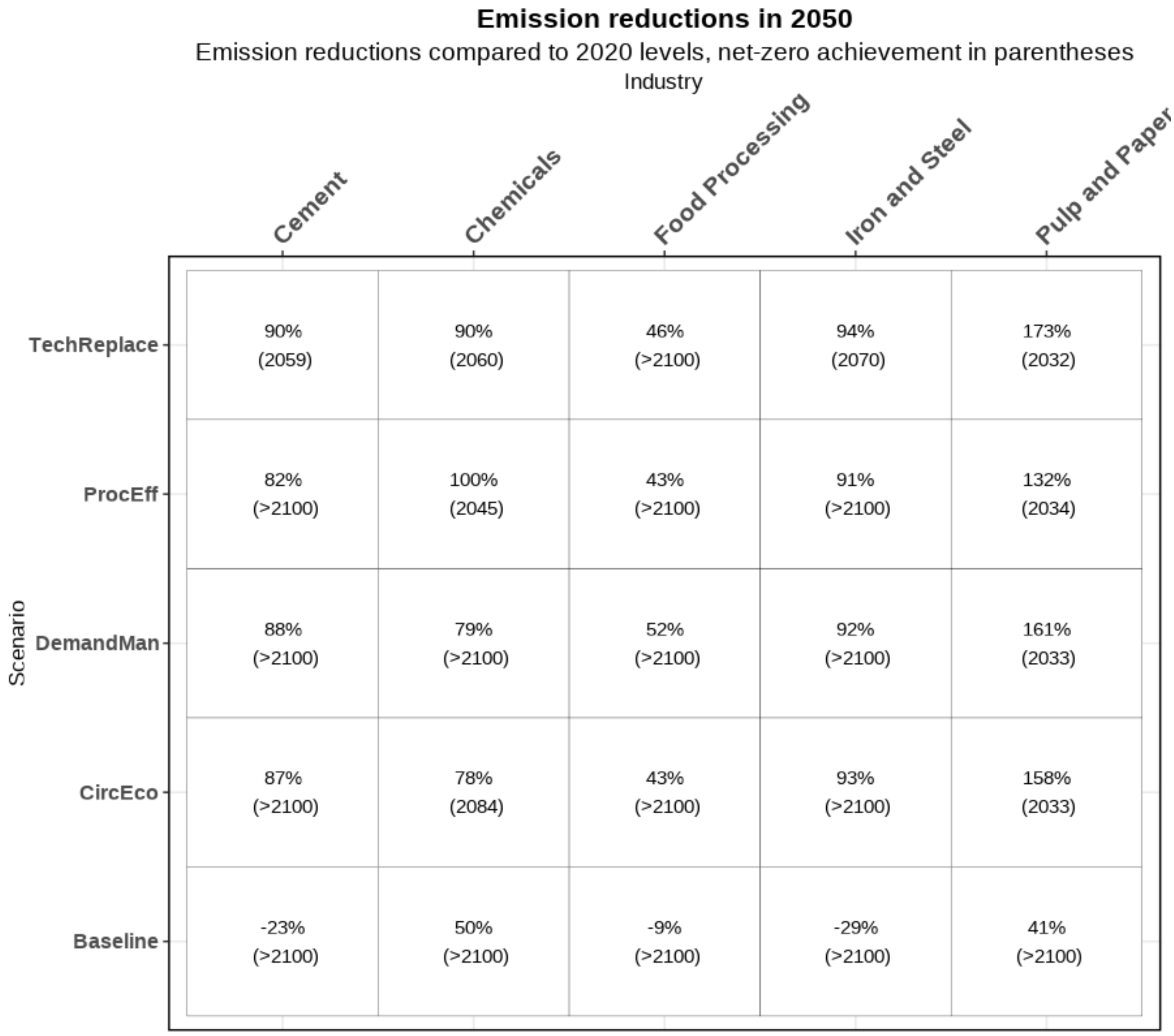

Figure 6 - Overview of goal achievement in 2050 per European industry and archetypical narrative

The total direct CO_2 emission reductions are indicated in a percentage. The year in which the net-zero goal is met is indicated between parentheses. If the objective is not met within the time horizon of the IMAGE model, this is indicated by „>2100“

3.1.1 Carbon capture and removal

By 2050, the IMAGE model projects that the European economy as a whole can limit the accumulation of carbon emissions to 50 Gt CO_2 since 2020 while sinking about 20 Gt CO_2 (see Figure 7). Although the differences are marginal across the narratives, the results how that technology-oriented narratives imply a larger need to remove emissions from the atmosphere. This is underscored in the *DemandMan* scenario, showing a lower need for non-biological storage of emissions and a greater potential for biological storage via agriculture, forestry and land use (AFOLU) practices.

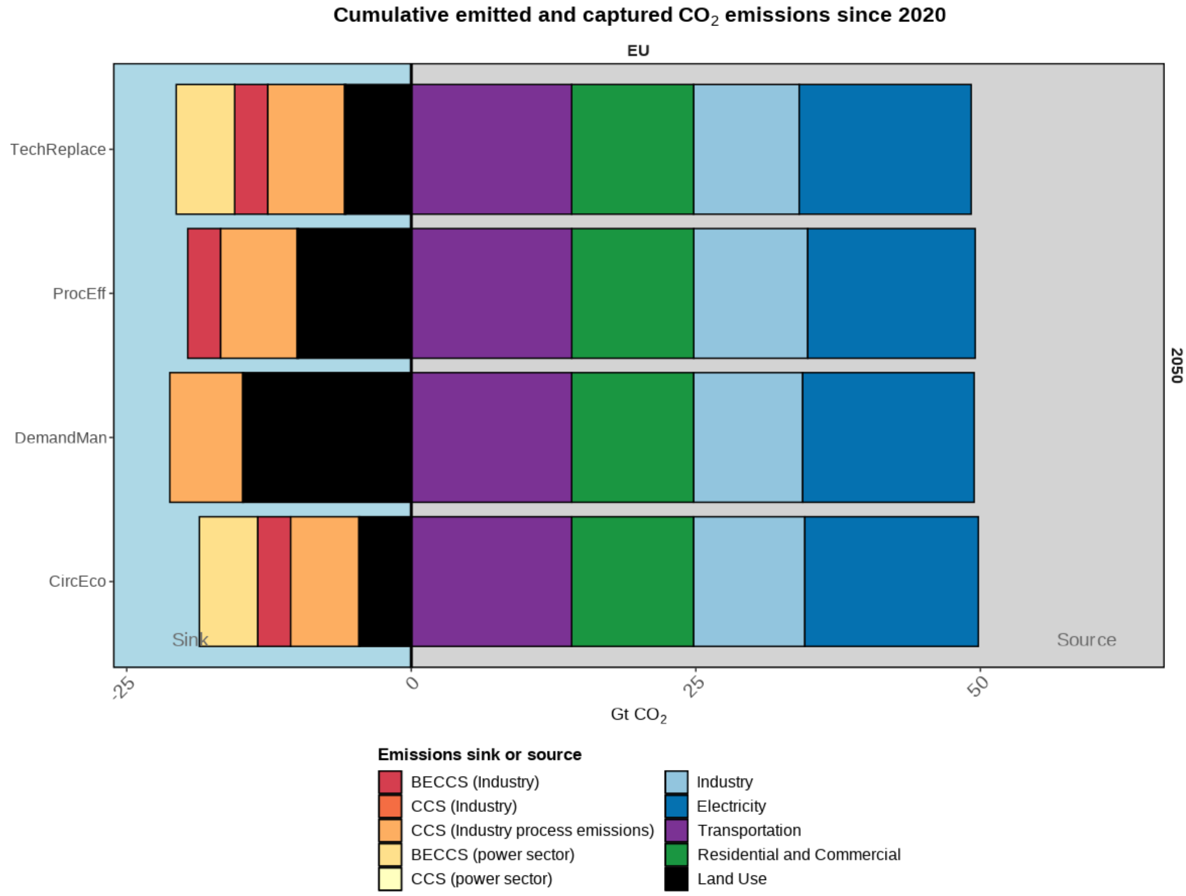

Figure 7 - Overview of total cumulatively CO_2 emissions in the 2020-2050 period per sector and the cumulative contribution for different sinks for the different scenarios

3.2 Material production and consumption

3.2.1 Primary production and consumption

The IMAGE modelling framework includes representations of total material demand and production to varying degrees of explicitness. Given how most of the material demand is driven by core socio-economic parameters exogenously, the main result is a gradually increasing material demand over time due to anticipated population and economic growth. Limited influence of climate policy on material consumption is included unless explicitly enforced through the archetypical narratives.

This becomes visible once looking at the more technology-oriented narratives (*TechReplace* and *ProcEff*), as steel and cement demands are expected to grow (steel by a quarter and cement by a third compared to 2020 levels) (see Figure 8A and D). For the (petro)chemical industry there is an overall decline in refinery products, but the demand for primary olefin production remains more-or-less stable over time. An imposed time-factor (emulating a decoupling of demand with economic growth) assures a decline in total paper product demands. The food industry is a more inelastic, maintaining more or less a similar total demand throughout the narratives (albeit with a little less food waste and switching to a greater consumption of staples).

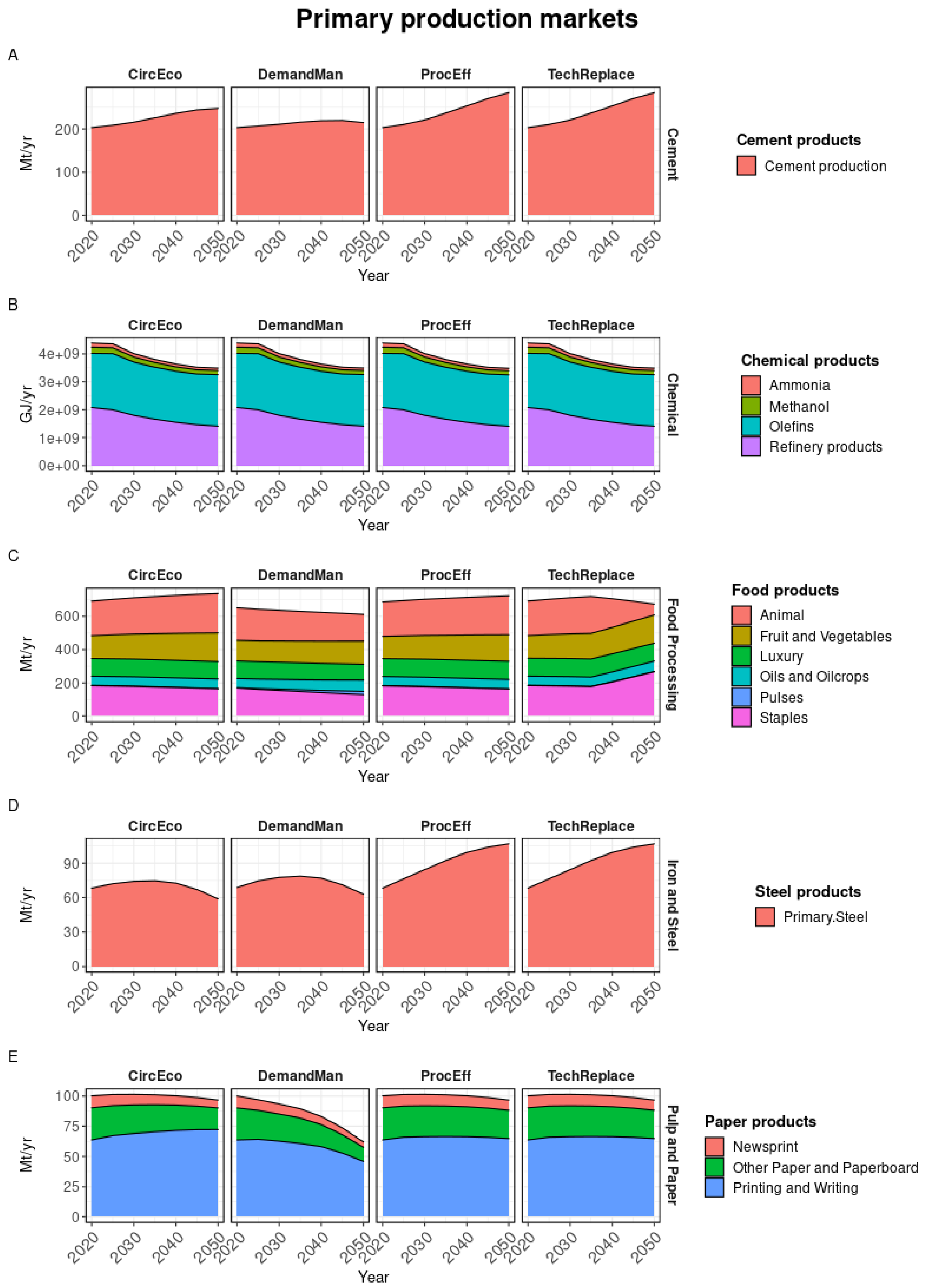

Figure 8 - European primary material production pathways for the REINVENT sectors and per archetypical narrative

The effectiveness of the archetypical narratives is visible in the consumption-oriented pathways (*DemandMan* and *CircEco*). Most of the increasing trends have been wavered off, stabilizing e.g. steel and cement demands by 2040 or sooner and eventually leading to a decline in consumption. The (petro)chemical industry remains on a similar primary production level as in other scenarios, showing a gradual decline. For pulp and paper, the total production and consumption of paper products is nearly halved in 2050 compared to 2020 levels. For the food production industry, a decline in total demand is visible due to less food wastage and a stricter diet reducing the intake of kcal/cap.

3.2.2 Secondary material production and consumption

Secondary material production markets have a stylized representation in the IMAGE modelling framework for only three industrial sectors (respectively steel, paper and the chemical industry). In general, similar growth patterns are followed as for the primary demand for the associated final products. As a result, the technology-oriented narratives (*TechReplace* and *ProcEff*) show an increasing market for secondary material for steel and paper over time, and subsequently a declining market for the *DemandMan* narrative (see Figure 9).

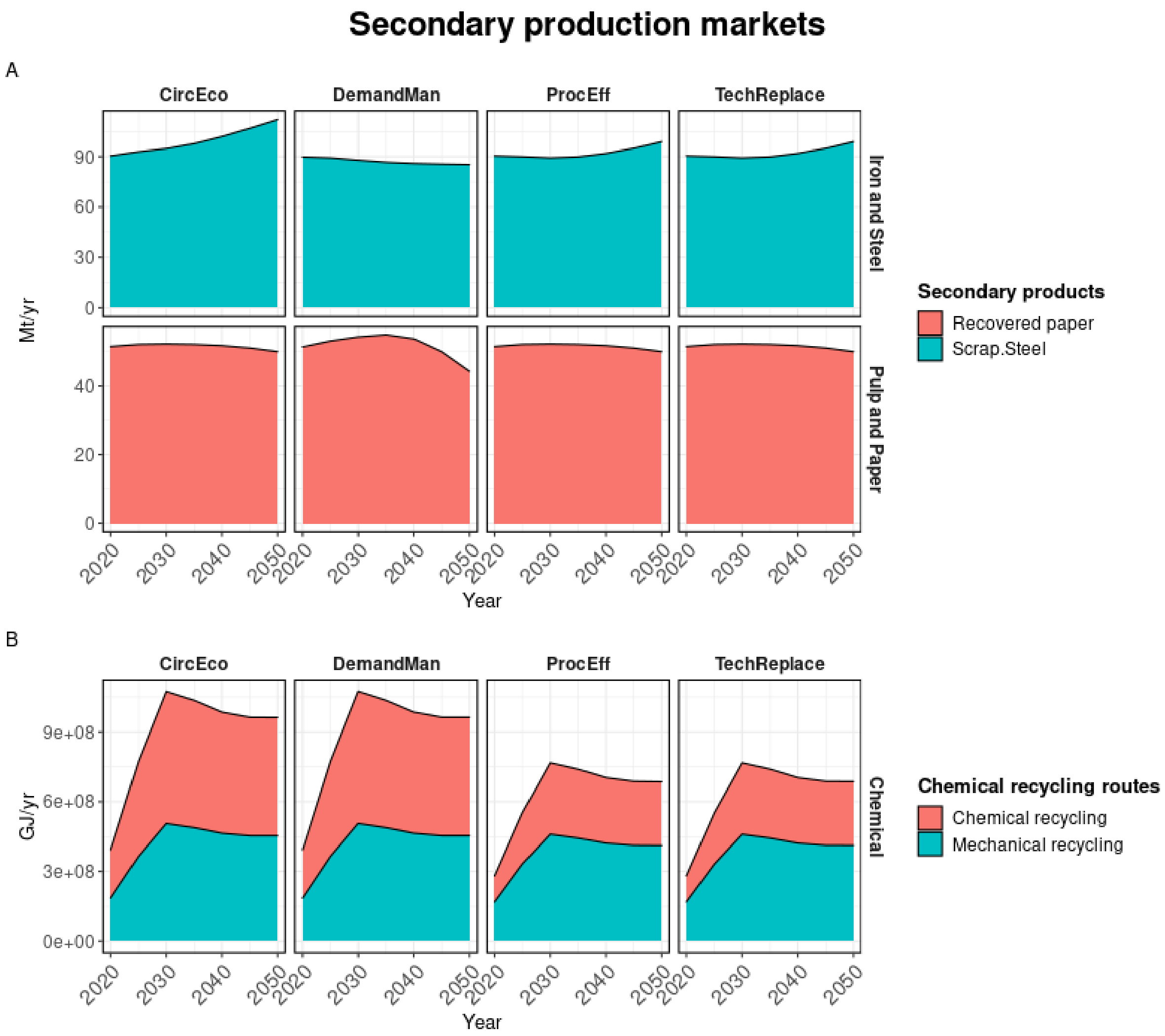

Figure 9 - European secondary material production pathways for the REINVENT sectors and per archetypical narrative

Due to the nature of the narrative, *CircEco* shows an increase in secondary material use in the steel and the chemical industry. Substituting primary feedstock for secondary materials shows to reduce the total demand for primary material in the steel industry (to a similar extent as *DemandMan*). For the chemical industry it implies no significant change as chemically recycled secondary material replaces virgin feedstock and does not change total demand for olefins.

3.3 Total Final Energy Consumption

Regardless of the narrative, total final energy consumption (see Figure 10) is shown to marginally decline for the first two decades, as opposed to the increase assumed under baseline assumptions. Total energy demand for the five scrutinised REINVENT sectors is assumed to decrease throughout the 2030-2040 period given a substantial decline in (gross[1]) energy consumption in the (petro)chemical sector. From 2040 onwards an increase in total final energy demand is shown again, particularly due to an increase in fuel consumption in the cement sector.

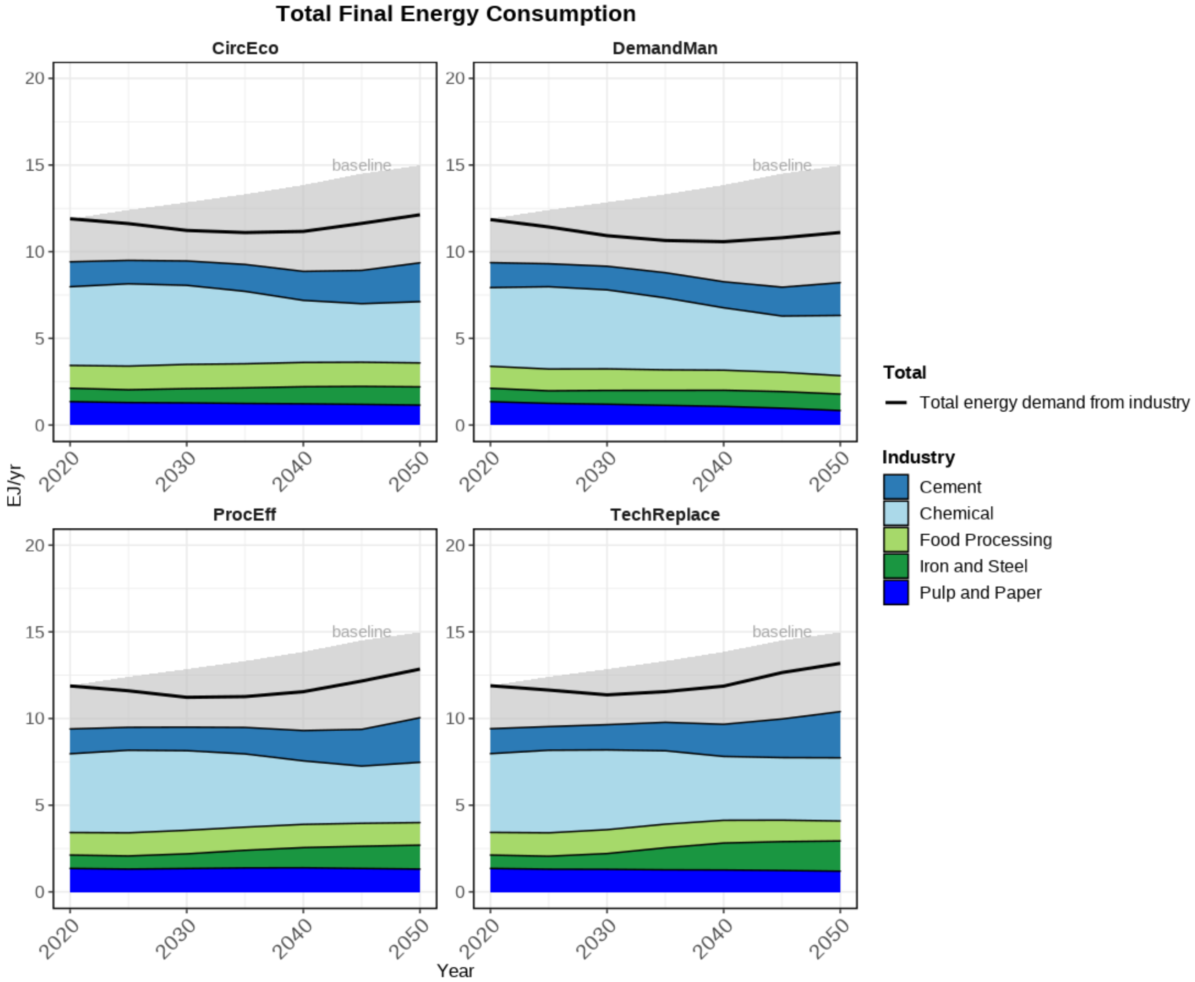

Figure 10 - Total final energy consumption for European industry and subsectors

The observed declines and increases can be further explained by looking into it at the level of energy carrier use (see Figure 11). The sharp decline in the (petro)chemical industry can be fully attributed to

[1] Gross energy use implies total primary energy use as both a feedstock and processing input

a declining demand for chemical commodities, particularly refinery products (as shown in Figure 8). An uprise in final energy consumption by 2050 is attributed to shifting to bio-based feedstocks.

Both the cement sector and steel industry are faced with increased energy consumption over time, as a result of increasing total primary demand for basic materials (as shown in Figure 8) and an energy penalty induced by specific technology choices (further elaborated on in chapter 3.4).

The food sector and the pulp and paper industries show a gradual switch to electricity-driven or biomass-fired production processes. *DemandMan* shows, as the only narrative, a declining energy demand due to a declining demand for materials (as visualised in Figure 8).

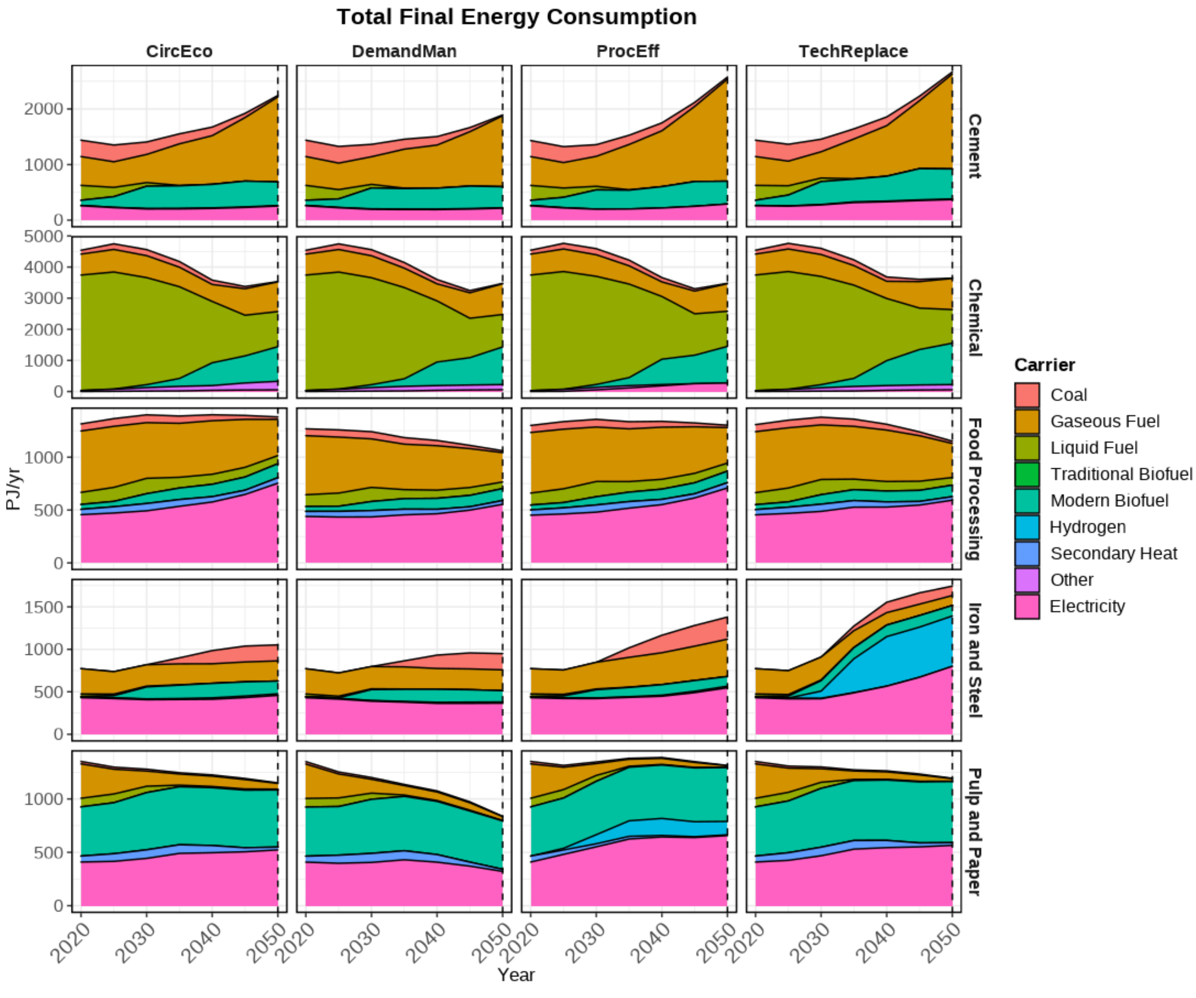

Figure 11 - Total final energy consumption for European manufacturing industries with specification of energy carrier

3.4 Production capacities

3.4.1 Steel industry

The European steel sector is characterized in IMAGE by a near 50/50 capital stock reflecting an integrated standard blast furnace (BF) and basic oxygen furnace (BOF) production route to cover primary steel production and an electric arc furnace production route covering secondary steel processing in 2020 (see Figure 12). The initial response under stringent climate policies is more or less similar across the different narratives: primary production routes remain primarily based on the use of metallurgical coal as the main reductant for iron making. As a result, the steel industries are projected to adopt more efficient BF technologies that are combined with CCS installations to capture remaining process emissions. A negligible share of inefficient and unmitigated BF/BOFs remain active towards 2050, but is to be completely removed from the European capital stock by 2060. A smaller share of alternative iron reduction routes is adopted throughout the narratives, which are either direct reduced iron (DRI) and smelt reduction (SR). In *TechReplace* a shift away from metallurgical coal is represented through the promotion of hydrogen (H-DRI) and electrochemical (electrowinning) steelmaking.

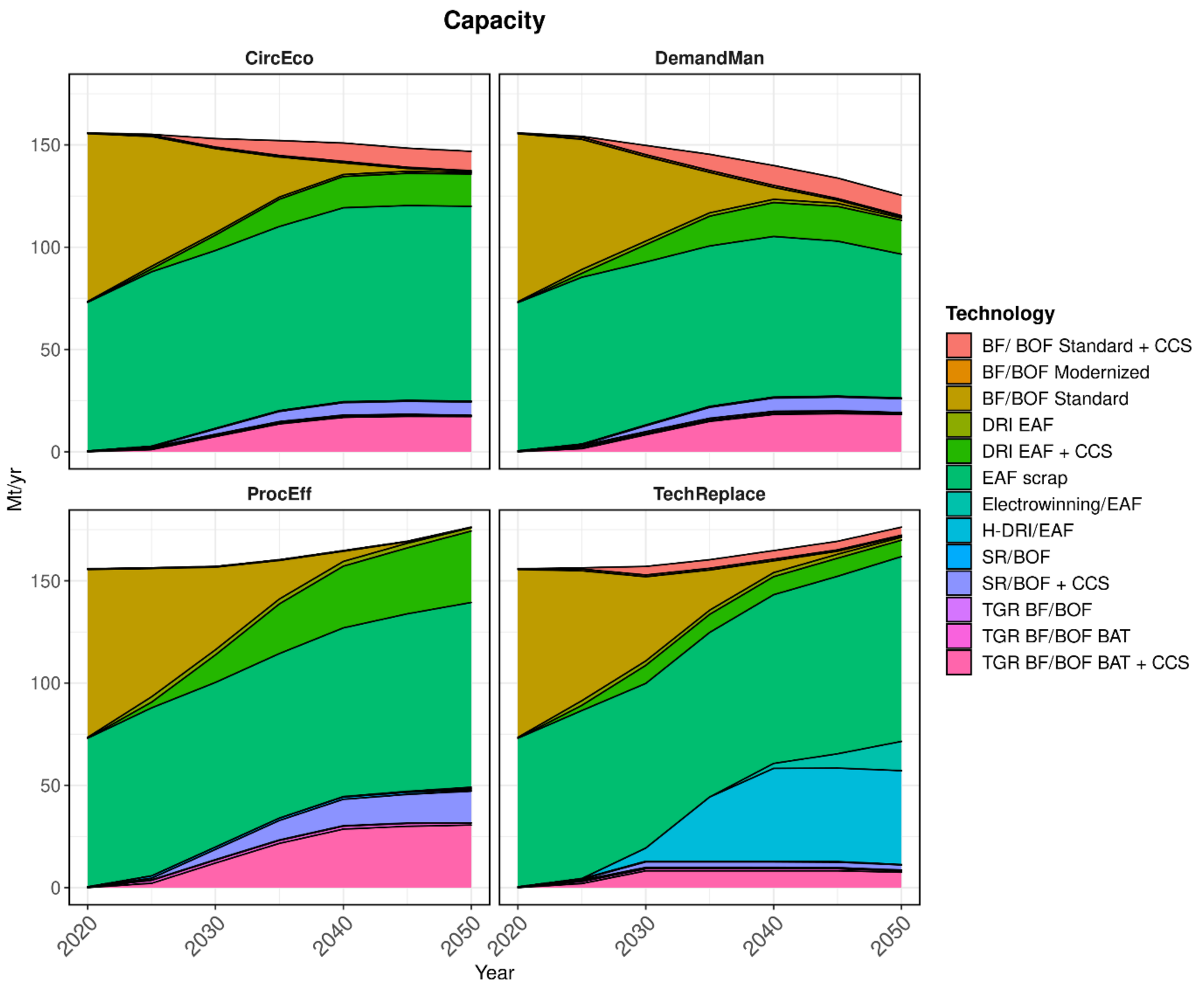

Figure 12 - Steel capacity for European steel industry per archetypical narrative

BF: Blast Furnace; BOF: Basic Oxygen Furnace; EAF: Electric Arc Furnace; DRI: Direct reduced Iron, CCS: Carbon capture and storage, SR: Smelt reduction; TGR: Top Gas Recycling, BAT: Best Available Technology

3.4.2 Cement industry

The cement industry is characterised by its use of the rotary kiln in the IMAGE modelling framework – fully utilizing a standard lime kiln in 2020 (described in more detail in Van Ruijven et al. (2016)). Under all decarbonisation narratives, the cement industry is projected to fully replace their unmitigated rotary kilns for more efficient ones that capture and store process and energy emissions. On the short-term this is based on the on-site CCS option, while from 2030 onwards the more efficient oxy-fuel based CCS option gain market share. With the exception of *ProcEff* – most of the narratives show that a small share of unmitigated lime kilns remain active towards and beyond 2050. This suggest that some residual emissions remain present in the cement sector. Some biofuel based rotary kilns are adopted allowing to partially offset the residual emission, though gas-fired rotary kilns remain present towards 2050 (see Figure 11).

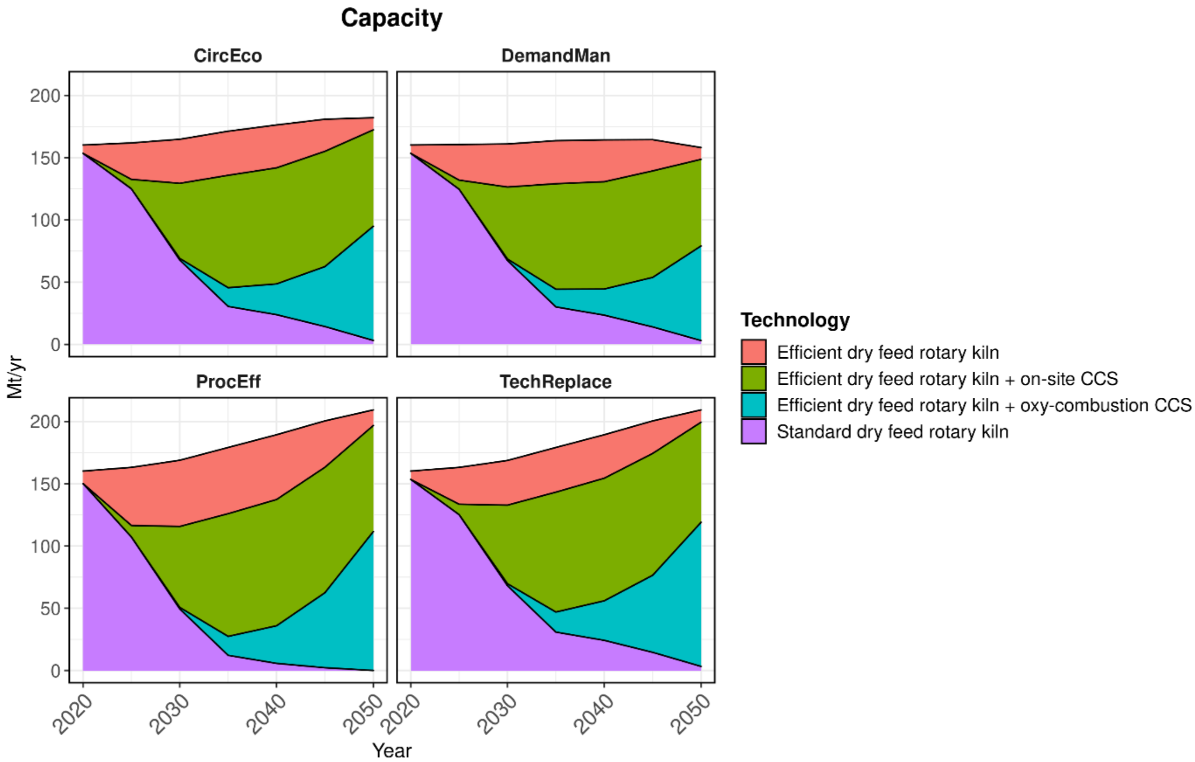

Figure 13 - Cement production capacity for the European cement industry per archetypical narrative

3.4.3 Chemical industry

The chemical industry is mostly characterised by producing olefins via naphtha steam cracking in 2020 in the IMAGE model. Regardless of the decarbonisation narrative, fossil-based feedstocks are rapidly replaced by biobased feedstocks (bioethanol or biomethanol) (see Figure 14). By 2050, most of the steam crackers have been phased-out and replaced by process reactors that can convert methanol or ethanol to polyolefins. For the *CircEco* narrative, carbon looping, chemical recycling and process integration with the pulping industry have become a more substantial part of the olefin production supply chain. By internally capturing the emissions of overall gas-fired processes, this allows the sector to reach net-zero emissions by 2080. *TechReplace*, assuming carbon looping but not process integration with the pulping sector, shows to reach net-zero emissions on a more timely scale due to lower competition for carbon looping, taking a larger market share more early on. *ProcEff* shows an early decarbonisation trajectory due to the adoption of electrified reactors.

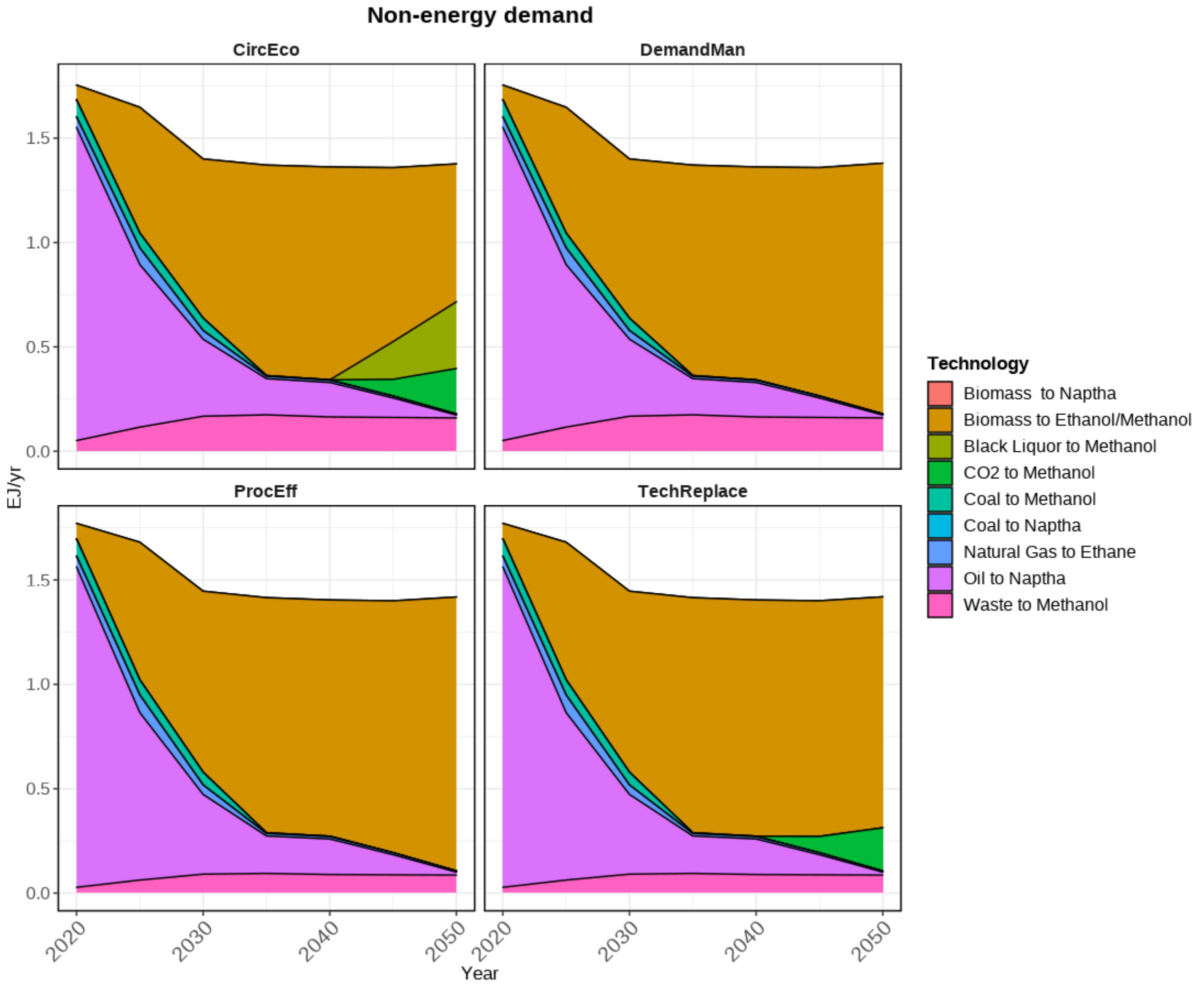

Figure 14 - Olefin production routes for the European chemical industry per archetypical narrative

3.4.4 Pulp and Paper industry

The pulp and paper industry is characterised in the IMAGE modelling framework by its heat demand for pulp and paper making. In 2020 most of the heat demand is fulfilled via the power boiler using the on-site residual biomass products and boilers running on fossil fuels. From 2025 more distinct differences are made visible for the technology-oriented narratives (*TechReplace* and *ProcEff*), focusing respectively on the use of CCS or a more diversified heat supply via the adoption of CHP and heat pump technologies. The consumer-oriented narratives show broadly similar technology changes, albeit under a declining capacity for *DemandMan*.

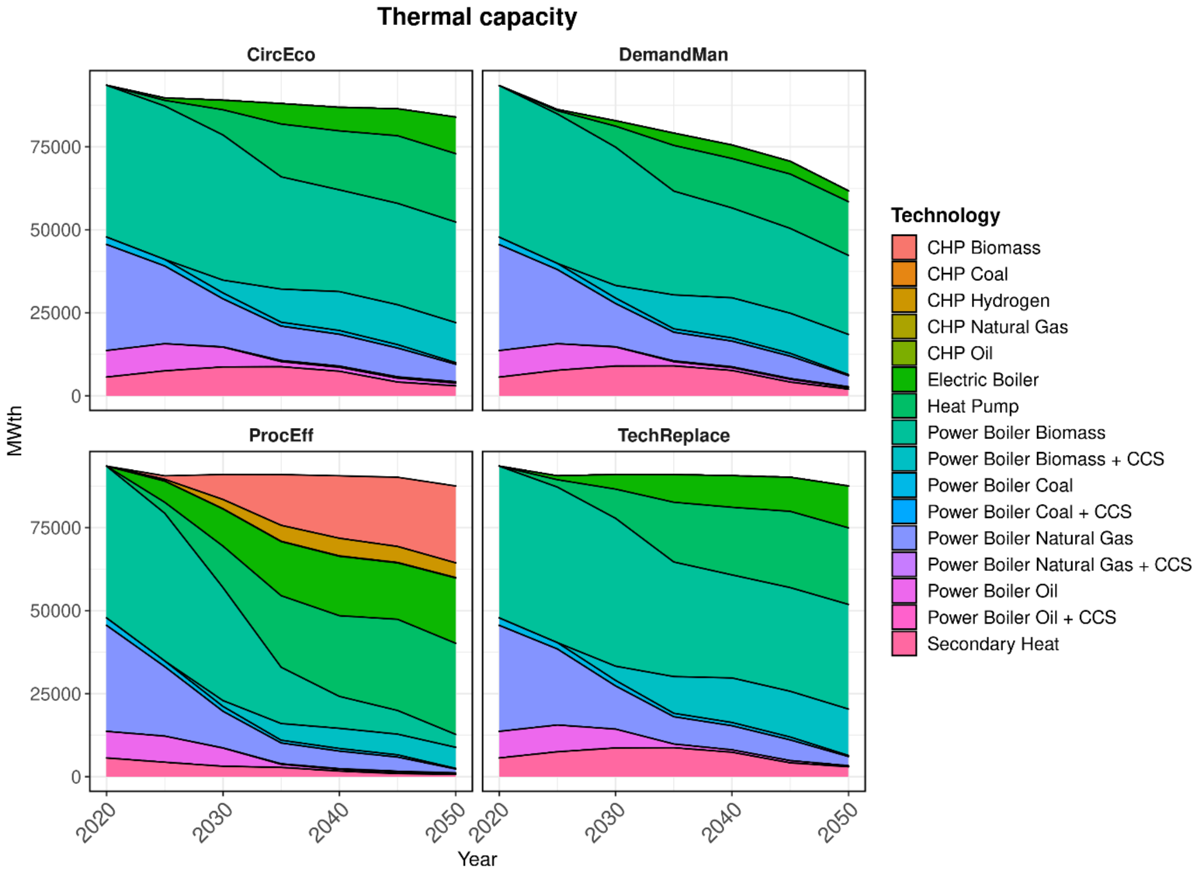

Figure 15 - Overview of thermal capacity for the pulp and paper industry per archetypical narrative
CHP: combined heat and power, CCS: Carbon capture and storage

3.4.5 Food industry

3.4.5.1 Agricultural system

The archetypical narratives developed for the food sector have an impact on the agricultural system and how it is deployed. All scenarios show an increase in cropland in Europe. This is partly driven by increasing welfare. The increase in scenarios with a dietary shift is marginally lower, as the increase in plant-food production is compensated by a stronger reduction in feed production. Pasture (used for livestock) decreases. Particularly the dietary shift narrative (*DemandMan*) results in more land being deployed for forestry (See Figure 16), resulting simultaneously in greater negative land use emissions for this scenario (see also Figure 7).

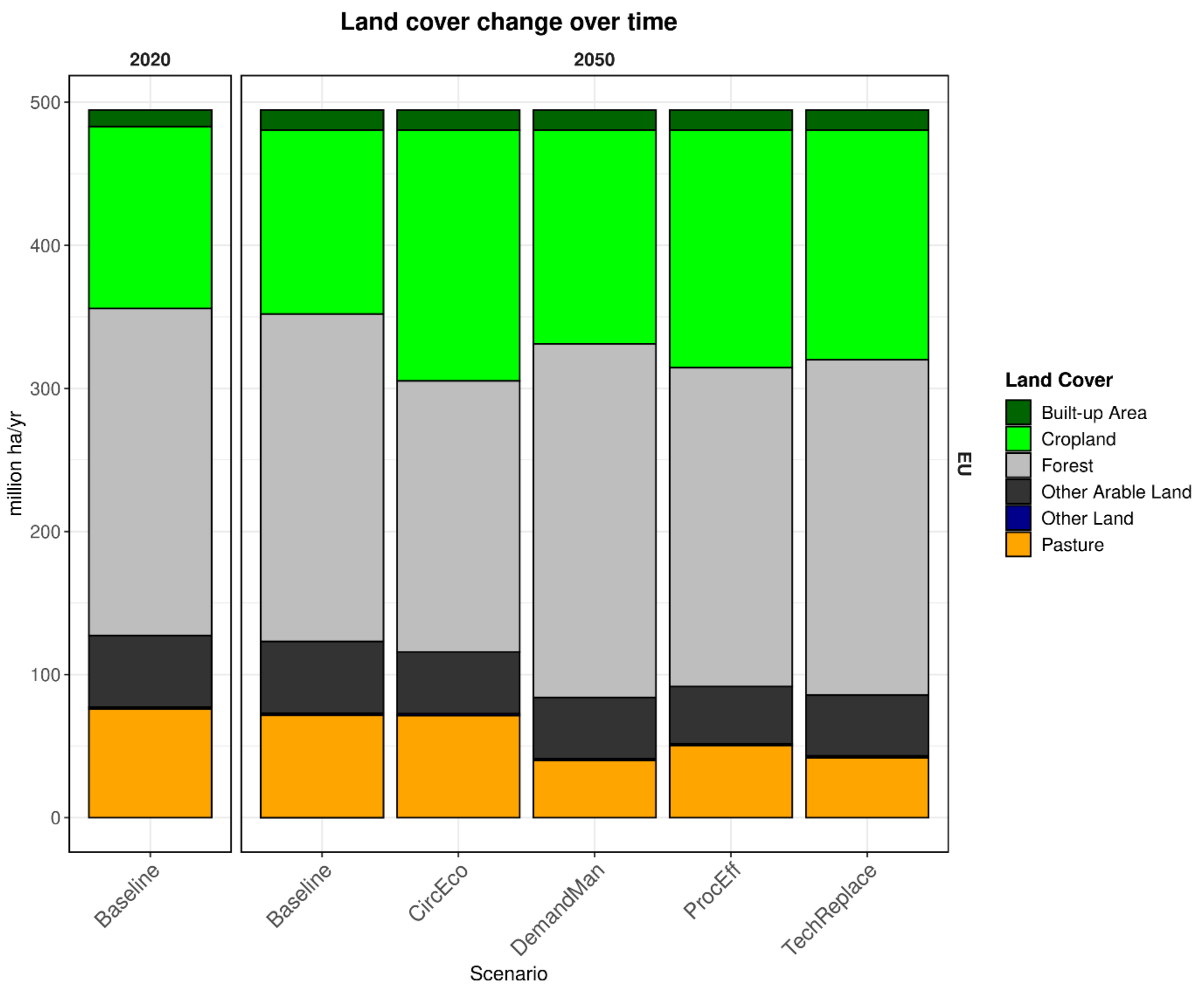

Figure 16 - Land cover change over time for Europe per archetypical narrative

In terms of agricultural systems efficiency, all archetypical narratives show to reduce methane emissions from livestock over time (see Figure 17). The dietary change narrative (*DemandMan*) shows to mitigate methane emissions from enteric fermentation and manure the most over the short-term due to the immediate adoption of a healthy diet. The narrative following technological advancement in food and agriculture (*TechReplace*) is projected to lead to a similar methane emission reduction (50%) by 2050 compared to 2020 levels as *DemandMan,* albeit with a larger cumulatively emitted budget over time.

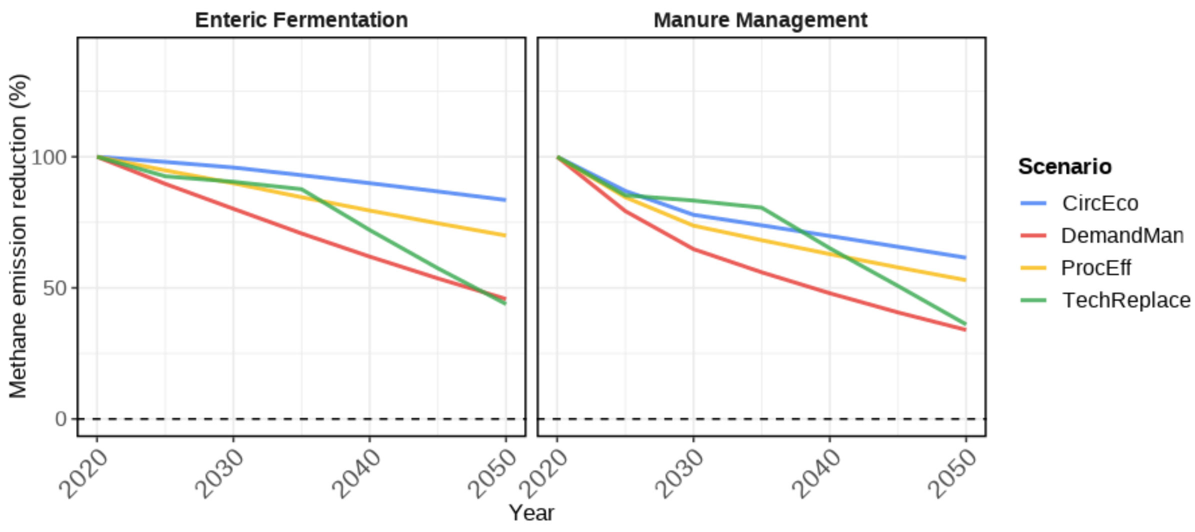

Figure 17 - European Livestock efficiency represented by methane emissions through enteric fermentation and manure management

3.4.5.2 Food processing

Overall, the capacities related to heat production remain broadly similar across the archetypical narratives (see Figure 18). The natural gas power boilers are projected to maintain a significant share in heat production throughout the first half of the century. The heat pump starts taking a gradually expanding market share for lower temperature heat demand from 2025 onwards. Electrification of higher temperature heat supply starts in 2040 with the gradually increasing adoption of the electric boiler. Switching the consumption patterns (*DemandMan*) or feedstocks for foods (*TechReplace*) influences the total demand for food and total demand for energy.

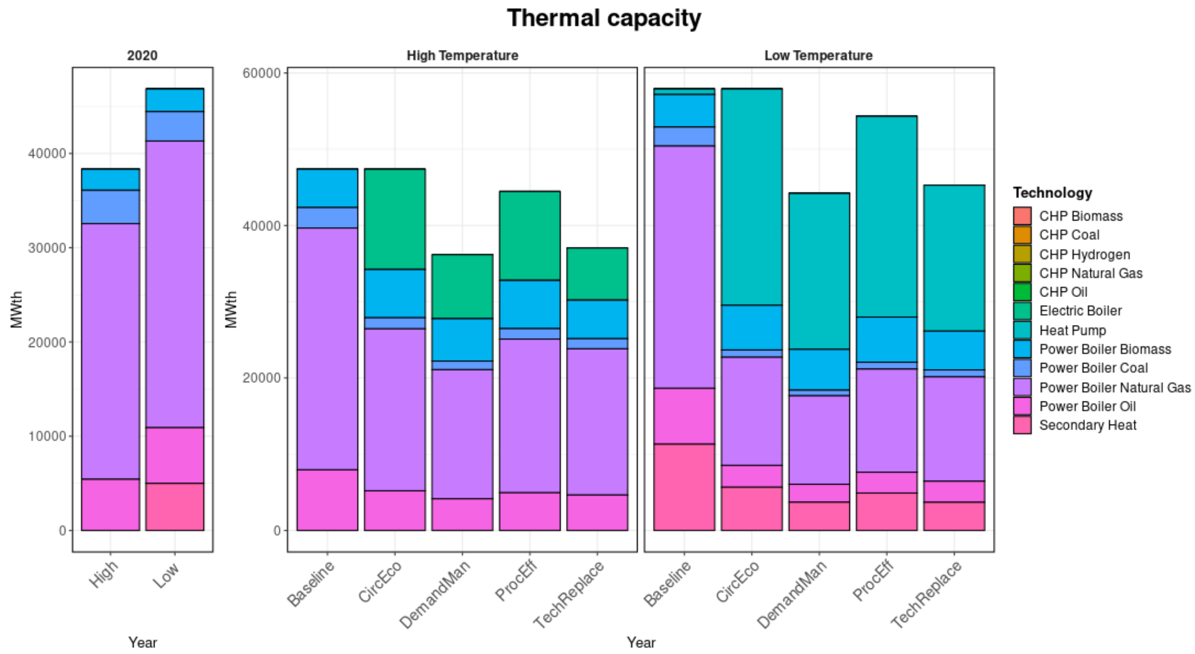

Figure 18 - Overview of the thermal capacity in the European food processing industry per archetypical narrative in 2050

4 Discussion

In this deliverable a set of long-term strategies to decarbonise five industrial sectors – steel, cement, plastics, paper and meat and dairy – have been assessed. In this section we reflect back on the process of tailoring various narratives of decarbonisation to the IMAGE integrated assessment model and discuss potential avenues for further research.

4.1 Integrated assessment

The projections presented in this report are limited to the model resolution as provided by the IMAGE modelling framework – hence the presented mitigation potential is based on those elements that could be included into the model. Several considerations about the presented decarbonisation pathways need to be kept in mind. We will elaborate on this in the following sections.

4.1.1 Conflated representation

The industrial systems represented in the IMAGE integrated assessment model are conflating the associated industrial value chains to the most energy intensive element of the production system. As a result, most of the strategies imposed by the model revolve around changes to an existing (production oriented) system that focuses, for example, on a blast furnace (steel industry) or lime kiln (cement industry) configuration. Innovations that move away from these existing processes are more difficult to fit into the narrative, henceforth leading to a conservative depiction of the decarbonisation potential for this sector.

Simultaneously, by conflating the production processes, it also obfuscates the possibility of intermediate states and decarbonisation potentials. For example, the current representation of the (petro)chemical industry in the IMAGE model only assumes start and end states in the production process for (petro)chemical products, but not the intermediates. For example, the model assumed various MTO production routes, yet does not explicitly account for methanol as an intermediate product. The dynamics of the plethora of associated (market) interactions are then not taken into consideration in this study.

Thirdly, due to the narrow focus of the most energy intensive element in the value chain, the IMAGE model has a certain bias towards up-stream production processes. Although some recycling feedbacks are explicitly modelled, implying a down-stream representation, these are generally static in nature and mainly to impose a decrease in primary material demand. Actual demand responses from the consumer side, or other circularity concepts than recycling, are therefore limited represented in the model and only approached through ad-hoc implementation of narratives. The extent of the decarbonisation potential throughout the industrial value chain as a whole are therefore largely unknown.

Lastly, conflated representation may also overestimate the decarbonisation potential as several challenges are not properly represented. For example, recycling systems may face various challenges in maintaining the quality of secondary materials with each successive recycling cycle. This is the case for steel scrap (Bowyer et al., 2015) and plastic waste, requiring near-pristine input in the form of uncontaminated, singly used plastics to maintain the thermal and mechanical properties of the material (Rahimi and García, 2017). Similarly for assumptions about (post-combustion) capture technologies, which cannot be applied uniformly across each material processing sector as capture rates vary due to differences in pureness and concentration (e.g. up to 95% in cement (IEA/CSI, 2018; Leeson et al., 2017), 8-65% in iron and steel, 8-50% in petroleum refineries, or 62-74% for pulp and paper) (Leeson et al., 2017).

4.1.2 Limited integration

The archetypical narratives have been implemented fairly locally, focusing on the individual contributions of each represented material processing industry. As a result it now includes an insular focus, despite representing intertwined value chains that touch upon many other facets of the economy. By representing only limited cross-sectoral integration, two major areas of development are then not taken into account: (1) process integration and (2) response effects of the rest of the economy.

Firstly, although the IMAGE model takes some process integration into account (such as representing the use of alternative cement binders, drawing from the power sector and steel industry, or methanol productions using black liquor from the pulping sector), many other potential interactions are not accounted for. Particularly the chemical sector is considered a linking pin in multiple visions about decarbonisation – being able to utilize multiple industrial residues and waste products as feedstock for chemicals. This strategy is now underexplored.

Secondly, in terms of response effects of the rest of the economy, all other demand sectors in the represented economy of the IMAGE model operate in a similar way throughout the various narratives. No information about changing industries feeds back into e.g. the transport sector or residential sector. This restricts the systemic assessment of consequences and impacts of industry decarbonisation strategies on the rest of the economy, potentially over or underestimating e.g. energy trade-offs (Deetman et al., 2020) or synergies.

4.1.3 Unexplained events

The carbon tax is not the only driver of change – as several narrative-based measures assume additional ambitions to create a levelized playing field. For example, more innovative production processes could not compete on costs and merit alone to the existing capital stock with carbon capture and storage retrofitting under an increasing carbon tax. This is particularly the case for the technology pathways adopted in *TechReplace*, for which a cost reduction has been forced for H-DRI and electrowinning (steel industry) and for the utilization of carbon or other substances in the chemical sector. Additionally, in the current implementation, hydrogen steel making is depending on market hydrogen. The IMAGE model is not able to render green hydrogen production as economically feasible under the current techno-economic parameterisation – hence most of the H-DRI capacity is driven on the use of blue hydrogen instead (natural gas). The need for such complementary policies and financing structures have been frequently mentioned as additional requirements for radical adoption of new technologies (Åhman and Nilsson, 2015; Bataille et al., 2018) but are not further specified in our assessment.

Similarly, the multiple social transitions that reduce total demand of materials, either via lower consumption or via higher efficient recycling and reuse systems, remain broadly unexplained within the IMAGE integrated assessment model. As emotion and cultural values influence the adoption rate of innovation, particularly prominent in the food sector, even than any other domain (Siegrist and Hartmann, 2020), this would require further research on the feasibility of these assumptions.

4.2 Future research areas

The portfolio of emissions-reduction strategies for industry presented in this study is limited to what could be represented in the IMAGE model, but does not represent the spectrum of potential as a whole. This section discusses known innovations that could further increase the decarbonisation potential as presented in this deliverable.

4.2.1 Production side / upstream value chains:

4.2.1.1 Flexibility

The IMAGE integrated assessment model utilizes a multinomial logit formulation to choose the least-cost option from a list of options and maintains this choice throughout the formulated (economic) lifetime of that choice. As the lifetimes of the basic material production lines are estimated to be on average 15 (pulp and paper), 25 (cement and chemical) to 30 (steel) years, this creates a certain lock-in to the chosen installed production capacity. Further reduction potential could be achieved if retrofitting or early capital depreciation could be included as a decarbonisation strategy. Further research could be done at the refurbishment intervals of production lines and to what extent this could help in meeting net zero ambitions by 2050.

4.2.1.2 Steel industry

Given the increasing importance of recycling, and in order to represent closed-loop systems for the steel industry better, more information needs to be acquired on the impacts of containments on the steel quality and methods to remove residual elements in scrap steel. Distinguishing for the qualities of the scrap may lead to a better representation of the cascading effects throughout the value chain. Novel insights on secondary material productions routes could be pursued, e.g. via studying innovative electric arc furnaces and pre-treatment processes (Daehn et al., 2019).

Secondly, another promising but poorly explored mitigation option is the use of less emissions intensive materials. The use of todays' common basic materials for planned (infrastructural) applications locks a large share of the remaining carbon budget (Müller et al., 2013). To prevent that from happening alternative low-carbon materials need to be considered. Several initiatives exist to date that present a proof-of-concept for replacing steel and cement by timber in e.g. buildings (Moore, 2020) or wind turbines (Hill, 2020).

4.2.1.3 Cement industry

A similar pathway can be pursued in the cement sector, showing potential for replacing Portland cement with low-carbon supplementary cementitious materials (SCMs). By adopting alternative low-carbon binders (e.g. alkali-activated materials, geopolymers, and calcium sulfoaluminate cements), it prevents the use and subsequently release of carbon emissions from clinker production. Alternatively, the IMAGE model has not looked at including a secondary material route, while waste management and recycling could add to the achievable reduction potential in this sector (Coppola et al., 2018).

4.2.1.4 Chemical industry

Much of the decarbonisation narrative for the chemical sector is about the embedded carbon in the products and the circular management of carbon cycles (CEFIC, 2019). Carbon capture and utilization is therefore an appealing decarbonisation pathway for the chemical sector. The capturing part is well covered in literature, however the application fields of CO_2 are still poorly understood and total potential is fairly speculative (Hepburn et al., 2019). Subsequently, electrification is considered an important decarbonisation option for the chemical sector, yet not explored in great detail in the IMAGE modelling framework. Including more technological detail on so-called 'power-to-X' technology options (both to produce chemicals or steam) could add to the reduction potential in this sector.

4.2.1.5 Pulp and paper industry

The current representation in the IMAGE model assumes steam generation to fulfil heat demand; while several innovations for this sector consider other means of dewatering (such as ultrasonic, osmotic, microwave drying) or substituting water for alcohol in the production process (VNP, 2018a). Electrification is also considered important for the decarbonisation of the sector (VNP, 2018b) – expanding the decarbonisation portfolio of the IMAGE model with options to electrify heat demand may add to the mitigation potential.

4.2.1.6 Food industry

No circular scenario options are currently implemented in the food production in IMAGE. In reality, there is untapped potential for farmers and their cooperatives in this respect (EC, 2020). The ‚Farm to Fork' strategy by the European Commission (EC, 2020), part of the European Green deal, mentions several opportunities that could be further explored, such as advanced bio-refineries to produce bio-fertilisers, protein feed, bioenergy, and bio-chemicals as several opportunities that could be further explored in integrated assessment.

4.2.2 Consumption side / downstream value chains

4.2.2.1 Material stocks and demand response

In the current setup of the IMAGE model, material demand is projected via an assumed relationship between material demand (steel, cement, plastics, paper) and economic growth. This relationship is calibrated to historic activity data, but it does not explicitly account for the services provided by the materials (i.e. steel for construction, plastics for packaging, etc.). Since the current model does not account for the demand of material services, it cannot represent the impact of changed lifestyles on industrial energy demand and emissions of industry in a consistent manner. Furthermore, by including material service demand, aspects such as the lifetime and recyclability of existing material stocks can be better accounted for.

4.2.2.2 Recycling systems and end-of-life

Furthermore, by expanding the system boundaries from cradle-to-gate towards, cradle-to-grave or cradle-to-cradle, it would be possible to assess the energy, emission, and other environmental consequences of different materials by weighting different end-of-life options (recycling, re-using, land-filling, etc.). Specifically for the plastics industry the CCU potential depends on if carbon remains captured via its use in long-life products, recycling, land-filling or incinerating with CCS. The energy and emission mitigation potential of the end-of-life options ultimately depends on the demand of different services and the technologies used.

5 Conclusions

In this deliverable a set of long-term strategies to decarbonise five industrial sectors – steel, cement, olefin, paper and the food sector – have been assessed. The strategies revolved around four different archetypical narratives, being Technology Replacement, Process Efficiency, Demand Management and Circular Economy. These narratives have been translated into assumptions for the IMAGE integrated assessment model, as to consider the broader effects across the sector and the economy. With the limitations of the model and the knowledge of further decarbonisation potential in mind, the following conclusions can be drawn:

An ambition to decarbonise the industry sector in 2050 is confronted with large inertia in the industry sector.

In this study we have adopted a carbon tax that drives the IMAGE model to utilize its mitigation potential across all represented regions and economic sectors to the fullest by 2040. The results show that this leads not to a fully decarbonised industry sector in Europe by 2050. Although some sectors are shown to reach net-zero emissions before 2050 (such as the pulp and paper sector, as well as the chemical sector under a specific narrative), some residual emissions are left unabated.

By 2050, full decarbonisation of industries is in the IMAGE model only achievable under specific technology-driven pathways.

With the exception of the pulp and paper sector, most of the other material processing industries show to struggle to become carbon neutral by 2050. Most of the sectors either maintain a certain level of residual emissions throughout the second half of the century, or reach the net zero goal under specific technological configurations. These configurations either depend on the adoption of (super-efficient) carbon capture and storage equipment, driven by a high carbon tax, or optimistic assumptions about R&D and market adoption (which come additional to a carbon tax).

Consumption change narratives show to unlock non-technological decarbonisation potential.

In the food sector, dietary shifts to a healthy diet combined with reforestation show to be particularly effective in terms of decarbonisation. On the one hand it mitigates emissions at the source, while increasing the capacity for natural carbon sinks. For other industries demand management and circular economy narratives also show to be effective methods to cut down emissions on the short term. However, in the absence of more explicit representations of cross-sectoral demand responses in a decarbonisation context, these estimates may be considered highly optimistic.

Key innovations require additional drivers to be adopted into the energy system.

Several of the core celebrated new innovations in heavy industry are not adopted by the IMAGE integrated assessment model without additional support, even under the assumption of a high carbon price. Drawing from the current literature, todays' investment costs and performances offers insufficient merit for large scale implementation. This is particular the case for (1) low-carbon steel production processes (hydrogen or electrochemical steel production), (2) cracking of petroleum products (electric cracking), (3) utilizing carbon or other substances from industries in the chemical industry (carbon looping, black liquor gasification). Secondly, the industry poses great dependencies on the conversion sector in order to become decarbonised. Although the IMAGE model can render the power sector net negative in terms of carbon emissions under a high carbon tax, this is not to the case for (market) hydrogen (producing mostly blue hydrogen towards 2050). This implies the need for greater implementation efforts from governments and societies and further research on the needed market conditions and agency.

The archetypical narratives offer an opportunity to explore new model configurations beyond the energy-orientation.

Story driven scenarios offer opportunity to make material and process-driven innovations more explicit in an integrated assessment model. However, in the current configuration and build-up of the IMAGE integrated assessment model, several significant limitations persist in how decarbonisation strategies are represented for the industry sector and its associated value chains. Due to the overall up-stream focus and the inherent energy-orientation, it renders much decarbonisation potential unavailable for further assessment. Particularly (1) demand responses for material consumption, (2) process integration, (3) material substitution (4) material stocks and circular economy have been frequently considered throughout this report as strategies with limited representation. The electrification of heat supply has also showed to be a common factor across several industries, which is currently underrepresented.

Acknowledgements

The authors are indebted to Lars J. Nilsson (LU), Fredric Bauer (LU) and Stephen Ivan aan den Toorn (UU) for providing feedback on the overall representation of the decarbonisation narratives into the IMAGE model, or for providing insights on the decarbonisation potentials that have been utilized in this study. David Gernaat (PBL) and Jonathan Doelman (PBL) are acknowledged for providing assistance during the development and execution of the IMAGE model runs.

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