REINVENT – PROJECT NR 730053

EU decarbonisation scenarios for industry

Deliverable 4.2

Mariësse van Sluisveld, Harmen-Sytze de Boer, Andries Hof, Detlef van Vuuren (PBL Netherlands Environmental Assessment Agency), Clemens Schneider, Stefan Lechtenböhmer (Wuppertal Institute for Climate, Environment and Energy)

2018-07-04

Contents

List of Tables

List of Figures

1 Motivation and aims

Achieving the Paris climate goals (keeping global average temperature increase to well below 2 °C and pursue efforts to limit to 1.5 °C since preindustrial levels) requires efforts in all sectors worldwide. The literature assessing transformation pathways towards meeting these Paris climate goals (Clarke et al., 2014) show a near complete decarbonisation of the energy system by 2050. The power sector is considered the main contributor for decarbonisation over time, given its central position as energy supplier for all economic sectors, the opportunity to switch to renewable and carbon-free alternatives and the potential to function as a carbon sink. However, given the various challenges and the urgency of systemic transformations throughout the economy under the Paris climate agreement, it is of importance to consider possible transitions of other sectors in more detail as well. Given how low-carbon transitions in industry are relatively unexplored (see also deliverable D4.1), this deliverable will focus on the decarbonisation of industry in a broader systems perspective.

Deliverable D4.1 provided the trends of energy use and CO_2 emissions of the four REINVENT energy-intensive sectors steel, plastics, paper, and meat and dairy over the last few decades. The current energy use and emissions of these sectors relative to those of total and total industry provides the context of the relevance of these sectors in total energy use and emissions (Figure 1). Due to data limitations, for plastics total chemical industry energy use and emissions are shown. Furthermore, instead of meat and dairy, total food processing is shown. Keeping these restrictions in mind, Figure 1 shows that the four sectors are responsible for more than 70% of total industrial energy demand, with the highest demand from the chemical industry, followed by steel. In terms of emissions, however, the sectors cover less than half the industry total. Steel has by far the highest emissions of the four sectors, followed by the chemical sector. This shows that steel is emissions-intensive, whereas paper, food processing, and the chemical industry are very energy-intensive but less emissions-intensive. The four sectors together are responsible for about 18% of total energy demand in the EU and about 7% of total CO_2 emissions.

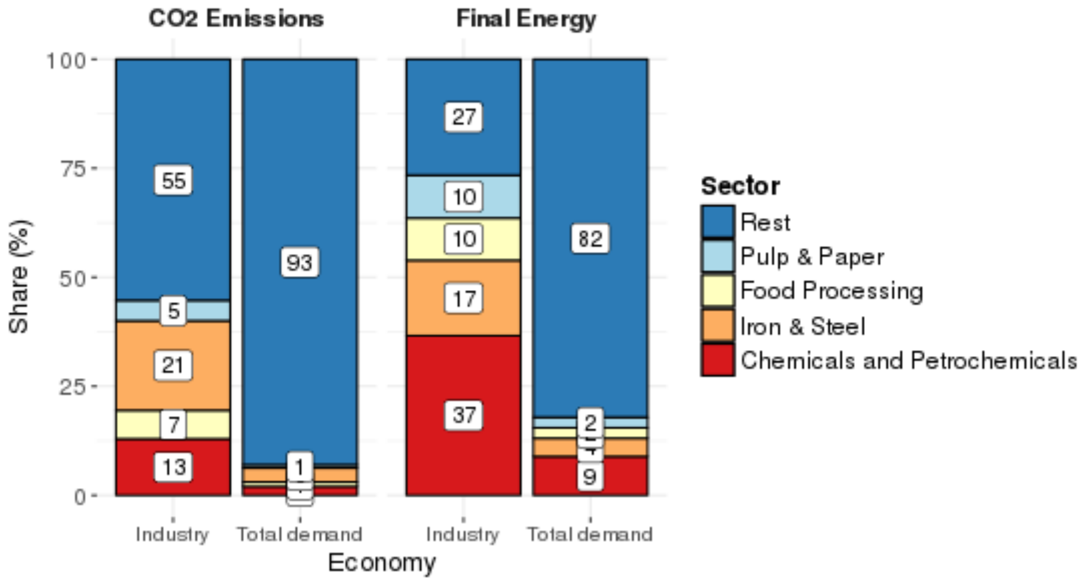


Figure 1. Current EU energy use and direct CO_2 emissions of the REINVENT sectors relative to total economy wide and industry totals.

Source: OECD/IEA (2017) and own calculations. Chemicals and Petrochemicals includes petrochemical feedstock.

This document provides an initial set of decarbonisation scenarios for the EU as a whole in a global context with emphasis on the four REINVENT energy-intensive sectors steel, plastics, paper, and meat and dairy. These scenarios were developed by the models in the REINVENT project and will be compared to existing scenarios which were discussed in deliverable D4.1. The scenarios have a strong focus on technologies and technology change and will serve the following purposes:

i) Show how decarbonisation by 2050 of the REINVENT sectors may be achieved;
ii) Provide input for the upcoming stakeholder workshops planned for the co-design and co-creation of decarbonisation pathways (Task 4.3);
iii) Provide input for discussion and analysis in the case studies of WP3.

In addition, this report provides information about the models used in REINVENT, how they interact, and how they model long-term transitions.

This report starts with introducing the four REINVENT industries and their current performance and the participating quantitative computational models (chapter 2). Chapter 3 continues by providing more in-depth descriptions of the causal chains and industry representations in the participating computational models in the REINVENT project. Chapter 4 describes the scenario assumptions used to align the assessment with the Paris climate objective. The outcomes of the assessment are presented in Chapter 5, and compared with the broader available literature in Chapter 6. The final chapter (Chapter 7) reflects on the findings and provides concluding remarks and recommendations.

2 Model descriptions

The decarbonisation scenarios as outlined in this report have been developed using two different models. The integrated assessment model IMAGE is used to provide insight in the consequences of the overall goal of the Paris climate Agreement on required changes in the REINVENT sectors, both globally and in Europe. The European engineering model WISEE is used to provide more detailed technology pathways. General descriptions of the two models used are given below. Section 2 provides more sectoral detail of how demand and supply is modelled for the separate industries and which technologies are taken into account.

2.1 IMAGE

The IMAGE modelling framework focuses on the chain of global environmental change for both climate and land use (Figure 2, Stehfest et al., 2014). Important inputs to the system are assumptions on population and economic development. The global energy system model IMAGE-TIMER (Figure 3) has been developed to simulate long-term energy baseline and climate change mitigation scenarios. The model describes the investments in and use of different types of energy options influenced by technology development (learning-by-doing) and resource depletion. Inputs to the model are macro-economic scenarios and assumptions on technology development, preference levels and restrictions to fuel trade. For food and agriculture, the IMAGE system uses projections made by the computable-general-equilibrium MAGNET model. This model describes, in interaction with the main IMAGE framework, changes in food production and trade for a broad set of crops and animal products.

Emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere are also simulated. Emissions from the energy system are calculated by multiplying total energy consumption per energy carrier with emission factors taken from the EDGAR database (JRC/PBL, 2014). The climate model MAGICC (Meinshausen et al., 2011) is used to project the future climate. World countries are grouped into 26 regions. Europe is represented by two sub-regions: Western Europe and Central Europe. Together, these regions represent the EU-28 and Albania, Bosnia and Herzegovina, Iceland, Liechtenstein, Macedonia, Norway, Serbia and Montenegro, and Switzerland.

Decarbonisation can occur via i) using less energy per unit of output or ii) switching to less carbon intensive energy resources. In general, the demand for products and services is assumed not to change in decarbonisation scenarios – although exogenous changes in demand could be assumed (e.g. changes in diet or reduced mobility). In most cases, the model is steered towards decarbonisation measures by introducing a carbon price in the model, which makes low-carbon alternatives more favourable. This carbon price should be regarded as a generic policy pressure leading to systemic behaviour oriented towards decarbonisation in line with a climate goal. Apart from this, climate policy can be introduced by explicitly setting renewable energy shares or efficiency standards.

Costs and cost developments are the driving decision factors in the model. Technologies with the lowest annualized costs gets the highest market shares according the following multinomial logit function:

$$MS_i = \exp(\lambda c_i) / \sum_j \exp(\lambda c_j)$$

Where *MS* is the market share of technology *i*, *c* are costs relative to the cheapest technology, and *j* competing technologies. *λ* is the so-called logit parameter, determining the size of markets to price differences. If available, these parameters are included with regional differentiation, although in most cases these are estimates assumed under generalizable conditions. Developments over time in terms of costs (cost curves, learning rates) or efficiency (learning rates) are important factors in IMAGE.

Efficiency improvement occurs both autonomously based on cumulative production (learning-by-doing) and by the introduction of an additional cost (e.g. carbon tax; price-induced energy efficiency improvement).

A detailed model description can be found at http://themasites.pbl.nl/models/image/.

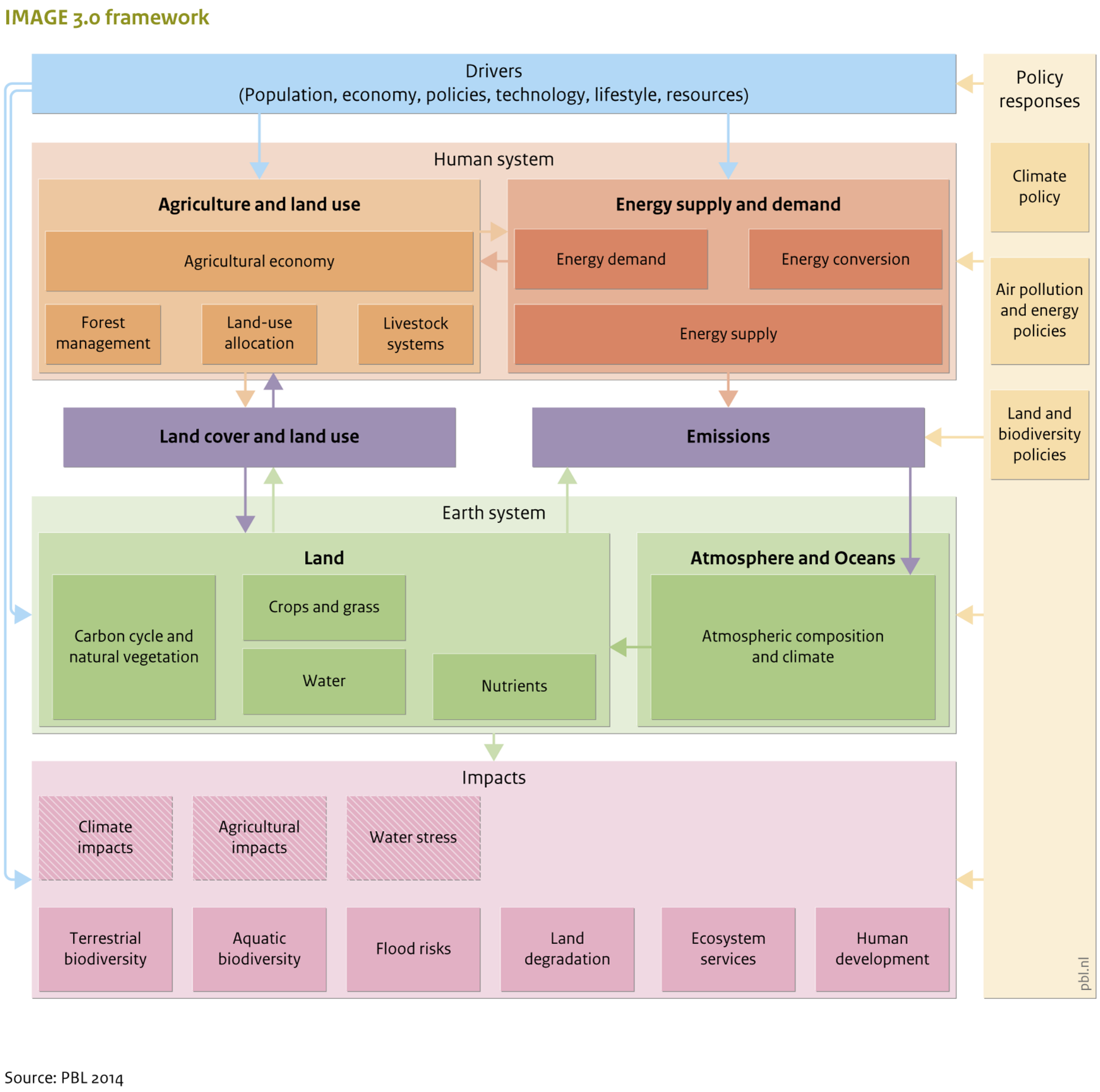


Figure 2. The IMAGE 3.0 framework

Source: Stehfest et al. (2014)

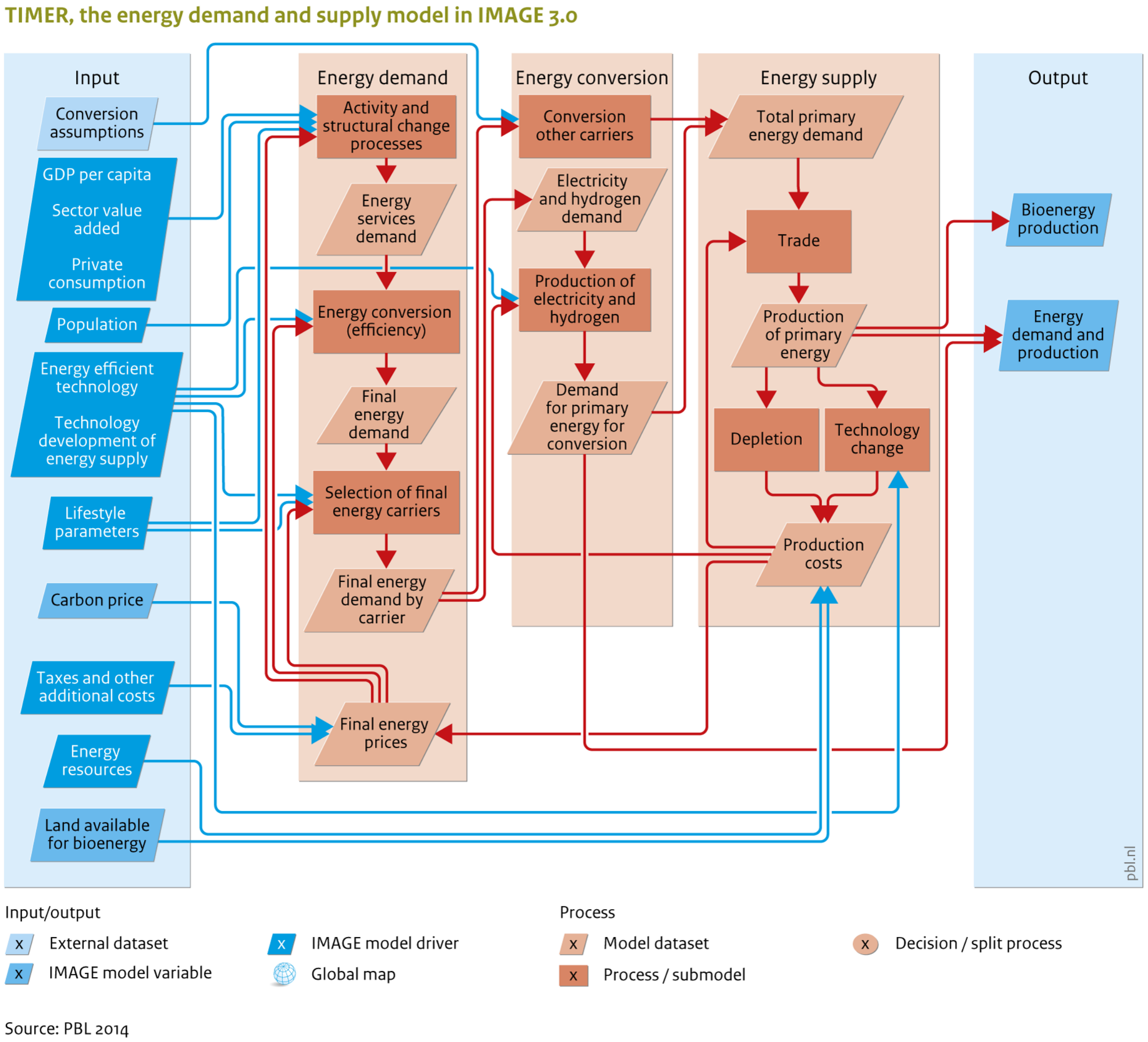


Figure 3. The IMAGE-TIMER model

Source: Stehfest et al. (2014)

2.2 WISEE

Wuppertal Institute's WISEE (Schneider et al. 2014) is a bottom-up energy system model representing production technologies in the context of value chains which are linked via product, energy and resource flows. It has been developed and validated within a stakeholder based scenario process supporting the development of the parliament's climate protection plan in the German federal state North Rhine-Westphalia (Lechtenböhmer et al. 2015). Following Herbst et al. (2012) the model can be classified as a bottom-up simulation model, with a very detailed representation of energy system technologies and a low degree of endogenization, i.e., many parameters can be changed by bringing in stakeholders' knowledge. Its focus is on unveiling existing energy efficiency and GHG mitigation potentials rather than finding the optimal pathway to achieve a given target (Hourcade et al. 2006).

The WISEE model explicitly covers manufacturing. Physical production volumes of products (in tons p.a.) are derived from respective sector scenarios or models. In REINVENT, physical production volumes are supplied by the TIMER/IMAGE demand modules, with the exception of plastics, where

WISEE needs explicit production (and waste) volumes to run the model (see Figure 4 and Chapter 3.3 for specifics). Energy demand is calculated by allocating the amount of the relevant products (including intermediates) on production stock (with different technologies over time) and multiplying with respective specific energy demand.

Emissions from the energy system are calculated in the same manner as IMAGE, i.e. by multiplying total energy consumption per energy carrier with emission factors taken from the EDGAR4.1 database. Apart from using less energy per unit of output and switching to less carbon intensive energy resources, WISEE has two other options for decarbonisation: by lowering production volumes and increasing recycling.

The EU industrial production stock is represented in a database with commissioning date, actual capacity and the production site (GIS coordinates). Site specification allows for an explicit analysis of by-products usage. Future technology choice is set exogenously in WISEE. Market shares of technologies during 5-years modelling periods determine the kind of stock exchange in production technologies. Future technology availability is an important factor in WISEE.

WISEE models the exchange of intermediates between industries and therefore innovations along the value chain may be addressed. These include synergies between hot rolling by hot charging and the use of by-products in the steel sector, and waste amounts (per plastic product), recycling of plastic waste and the whole manufacturing value chain from feedstock to polymer in the plastics sector, allowing for an explicit analysis of waste management / recycling options.

Figure 4 shows a stylized overview of the model. The power plant dispatch module is not used in the REINVENT project, neither are the modules for the non-REINVENT sectors used (like e.g. cement).

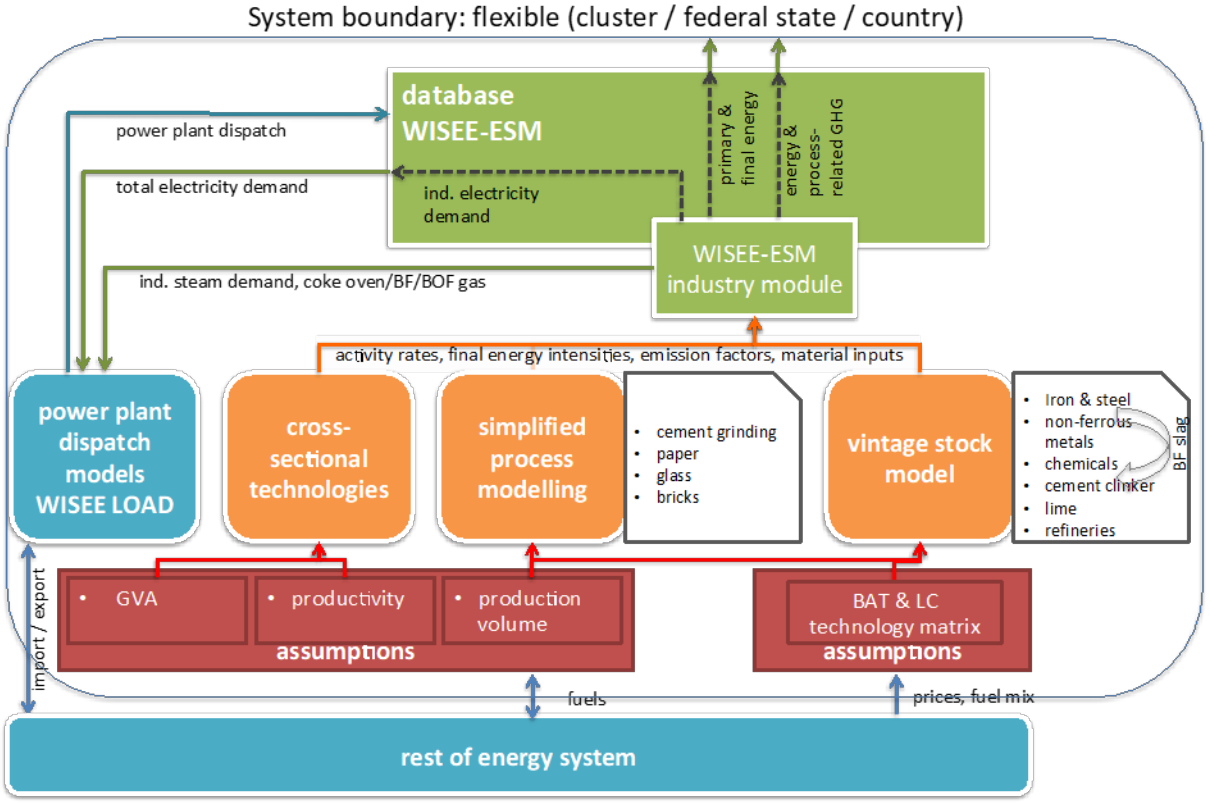


Figure 4. The WISEE model

3 Industry sector representations

3.1 General overview

Table 1 summarizes the representation of the different sector elements of IMAGE and WISEE relevant for REINVENT; an X denotes that the element is modelled endogenously (not an external input to the model). The detail at which the different sectors are modelled differ by sector, which is explained in more detail in the subsequent sections.

Demand for steel and paper is modelled in IMAGE and used as input for WISEE. For plastics, on the other hand, WISEE explicitly covers the value chain from the supply of base chemicals like olefins and aromatics via intermediates to polymer production. Note that WISEE does not have a representation of the food sector.

Table 1. Model elements in IMAGE and WISEE

Model elements	Steel		Chemical / Plastics		Paper		Meat and dairy
	IMAGE	WISEE	IMAGE	WISEE	IMAGE	WISEE	IMAGE
Demand/consumption	X	-	X	X	X	-	X
Production	X	X	X	X	X	X	X
Capital stock	X	X	-	X	X	-	X
Technology choice	X	Input	-	input	X	input	X
Trade	X	-	X	input	input	-	-
Secondary/recycling	X	X	-	X	-	X	-
Considered to be:	Detailed	detailed	detailed	very detailed	basic	basic	basic

X = the element is modelled endogenously (not an external input to the model);
input = external input to the model (e.g. historical trends or expert and stakeholder knowledge)

3.2 Steel

In the following section a more in-depth description is provided on the representations of the steel supply chain, total final energy consumption and emissions for the steel industry. More detailed information can be found in Van Ruijven et al. (2016) for IMAGE and in Schneider and Lechtenboehmer (2016) for WISEE.

3.2.1 Material and energy demand

In IMAGE, the demand for crude steel is modelled by deriving a relationship from historical per capita steel consumption data and per capita GDP, and extending this into the future (See Figure 3). The statistical model, reflecting a logistic growth curve with a decay factor (see Neelis and Patel (2006) for a more detailed description), is plotted through historical steel production data taken from the Iron and Steel Statistical yearbooks of 1980 (1970-1979), 1990 (1980-1989), 2000 (1990-1999) and 2001, 2002, 2003 and 2004. Historical population data is derived from UN statistics, and GDP from the World Bank (2010). The derived curve provides indication of the 'intensity of use' (IU) for steel specified per world region in the IMAGE model. Combined with the long-term population and GDP projections, which are exogenous trends to the IMAGE model (See Chapter 4), it provides a (static) estimate for crude steel that extends into the future.

In WISEE, no demand for crude steel is modelled; instead, material demand is taken from IMAGE.

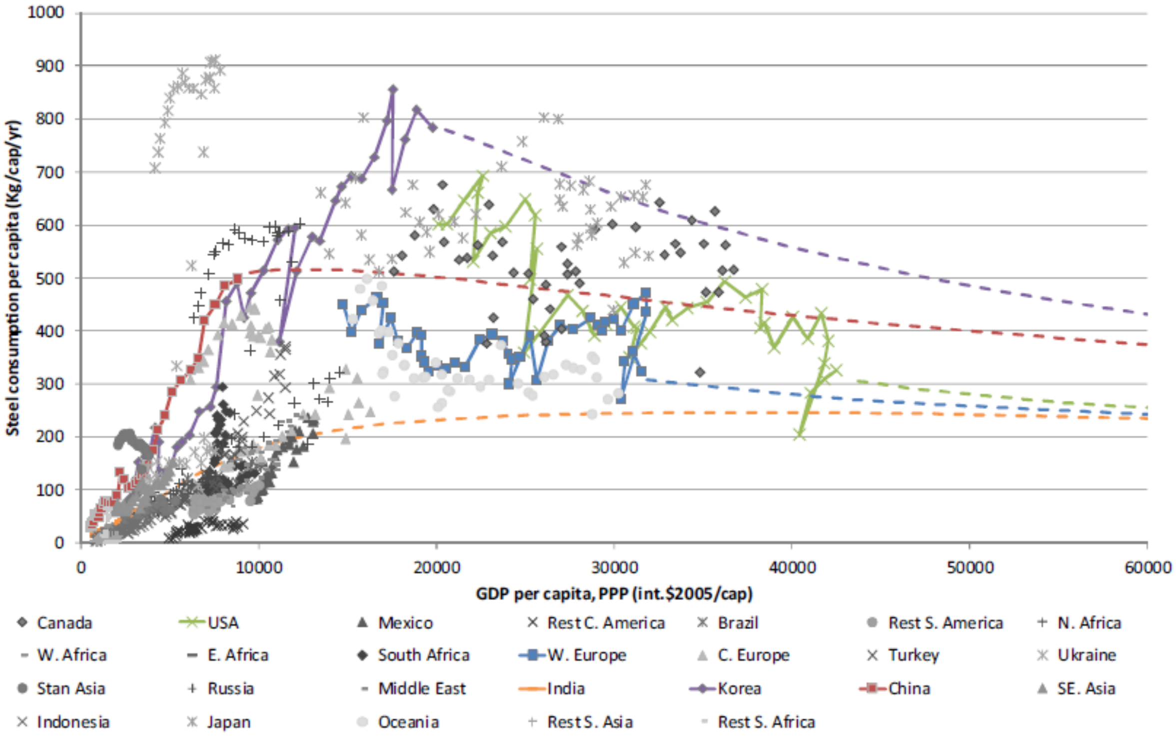


Figure 5. Demand curves extracted from historical data on crude steel consumption and income per capita

Source: Van Ruijven et al. (2016)

Total energy demand for crude steel production in the IMAGE model is derived from multiplying the total physical production volumes with specific energy consumption values as reported in literature (Van Ruijven et al., 2016). A further breakdown of energy demand across the included production technologies and energy carriers is described in the next section.

3.2.2 Production

In IMAGE, it is assumed that the demand for steel is being met by either domestic production or trade with other regions. This means that production by region is determined by the projected demand and steel trade between regions. The main drivers of trade between regions are the relative production costs per region, the transport costs between the main ports of the two regions, and a trade barrier factor between regions based on historic trade data and scenario assumptions (e.g. increased or decreased openness of economies).

Various routes are available to produce crude steel. While both IMAGE and WISEE have a comprehensive representation of the different chains of production for steel, IMAGE is a more aggregated model and hence the level of detail of WISEE is significantly higher and includes more technology options (see Table 2).

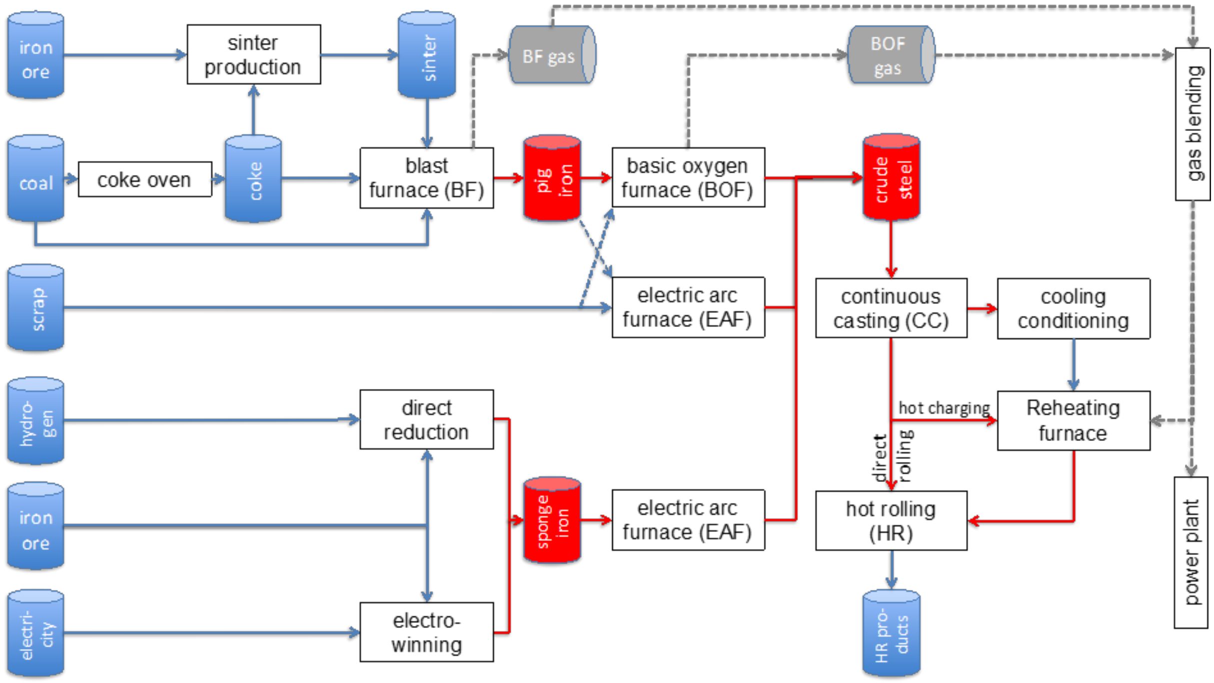


Figure 6. The steel supply chain in WISEE

Source: Schneider and Lechtenboehmer (2016)

Table 2. Production technologies of the steel sector in IMAGE and WISEE

Production routes and technologies	IMAGE	WISEE
Primary steel production volume	X	*
Secondary steel production volume	X	*
EAF + scrap	X	X
Standard Coal Blast Furnace + BOF	X	X
DRI with natural gas + EAF	X	X
DRI EAF route + CCS	X	
Efficient Coal Blast Furnace + BOF	X	X
Efficient Coal Blast Furnace + BOF + CO2 capture	X	X
COREX smelt reduction + BOF route	X	
COREX smelt reduction + BOF route + CO2 capture	X	X
DRI with hydrogen + EAF		X
Iron electrolysis + EAF		X
Gas fired ovens		X
Electric ovens		X
Recycling processes	X	X

EAF: Electric Arc Furnace, BOF: Basic Oxygen Furnace, DRI: Direct Reduced Iron
X = explicitly represented in modelling framework
* = provided by IMAGE model

In IMAGE, the relative market share of production technologies depends on total energy costs, annualized investment and O&M costs and other costs of the respective technologies as explained in Chapter 2.

The dynamic in the WISEE steel module results from stock reinvestment. Expiry of lifetime of existing stocks opens up the window for technological change. However, mothballing of stock before expiry of lifetime may be a specific strategy to speed up decarbonisation, which can be applied via a specific assumption. The allocation of energy carriers and production technologies in WISEE takes place in a four-step approach:

1. Overall EU production as provided by IMAGE is broken down to seven regional markets, i.e. UK, North-Western Europe, Scandinavia, Baltic, Eastern EU, Southern Europe and South-Eastern Europe using today's shares as an indicator.
2. Determining how much production technology has to be reinvested in the regions according to
    a. expiry of lifetime of existing stocks
    b. required production volume (derived from result of step 1; taken from IMAGE, based on the demand for steel from IMAGE and trade in steel)
3. Determining technologies to reinvest in. This is exogenously set according to the scenario storyline, but may differ between regions (i.e. member states) within the EU.
4. Determining the actual capacity utilisation, the respective energy demands and emissions.

For the steel sector, both IMAGE and WISEE use technology data from the World Steel Association. Apart from this, WISEE uses information from the WISEE industry database, Remus et al. (2013), and stakeholder information.

The availability of scrap metal is modelled explicitly in IMAGE by taking into account the lifetime of different kinds of steel usage, steel characteristics, and recycling rate limitations. Scrap is assumed not to be traded internationally due to lack of data.

3.3 Plastic

Here the key characteristics of how plastic demand and production is modelled are summarized; more detailed information can be found in Daioglou et al. (2014) for IMAGE and in Schneider et al. (2018) for WISEE.

3.3.1 Material and energy demand

In the IMAGE model, total demand for chemical products is based on a historical relation between the consumption of chemical products per capita and GDP per capita. A logistic growth curve is plotted through historical production data of the chemical industry from the Methanol Institute (1999-2003), OGJ (1997-2012a), OGJ (1997-2012b), and USGS (1996-2012) to derive an 'consumption per capita' formulation. By combining this curve with long-term population and GDP projections, which are exogenous trends to the IMAGE model, it provides an (static) estimate for chemical products that can extend into the future. This method yields regionally distinct demand curves for four aggregated chemical (intermediate) product groups (High value chemicals, ammonia, methanol and refinery products) without further detail on the end-use sectors.

Total energy demand for chemical products in the IMAGE model is derived from multiplying the total physical production volumes with specific energy consumption values as reported in literature. A further breakdown of energy demand over the included production technologies and energy carriers is described in the next section.

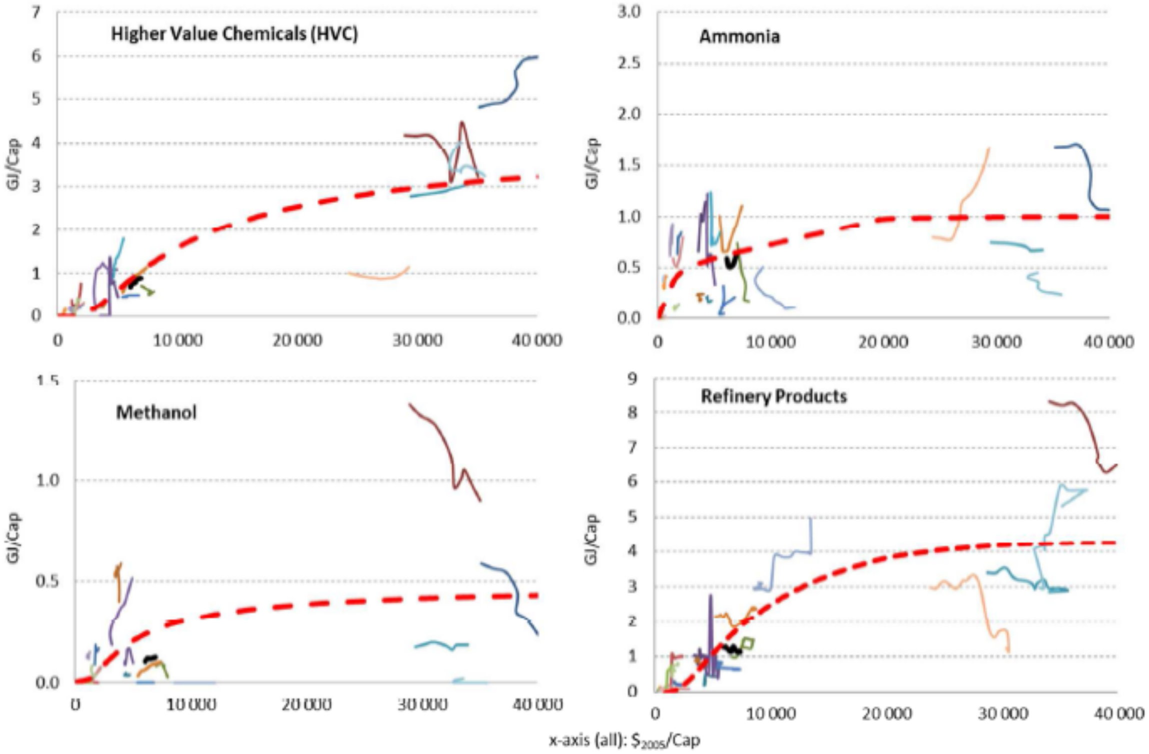


Figure 7. Demand curves identified for the aggregated chemical product groups in IMAGE

Source: Daioglou et al. (2014). The coloured thin lines represent IMAGE model regions, the red dashed line the IMAGE implementation.

The WISEE model has a more detailed representation of the plastics industry, which is able to represent the supply chain for 13 basic plastics[1] across five plastic conversion sectors (packaging, construction, automotive, electric and electronics, and other). Future plastics demand is based on the historical relation between consumption of plastics in Mt per gross value added and on the development of gross value added and trade volume. The demand of platform products is derived from plastics/intermediates demand (three sorts of olefins, three sorts of aromatics, chlorine and ammonia) and the demand of 22 intermediates is derived from plastics demand. WISEE also models the amount of waste based on typical stock lifetime of plastic containing products. Historical production is derived from Eurostat COMEXT and Eurostat Trade balances, while demand is based on annual statistical information from Plastics Europe.[2]

In total, this makes up a total matrix of 65 cells. These 65 cells are available for the past until the base year 2015 and have been extrapolated for each single scenario year by deducing total plastics demand of each branch and keeping the plastic sort structure on the branch level constant. However, as the demand extrapolation at the branch level differs between the branches, the total plastic sort structure changes over time as well.

---

[1] Polyethylene, linear low density (LLDPE), Polyethylene, low density (LDPE), Polyethylene, high density (HDPE), Polypropylene Polyvinylchloride , PET, polyurethanes, expanded polystyrene, polystyrene, polyamide, polycarbonate, ABS, PMMA and "other plastics" (the latter two not regarded in the analysis of production).

[2] Annual statistics ("Plastic – the facts") are available at https://www.plasticseurope.org/en/resources/market-data [25/06/2018],

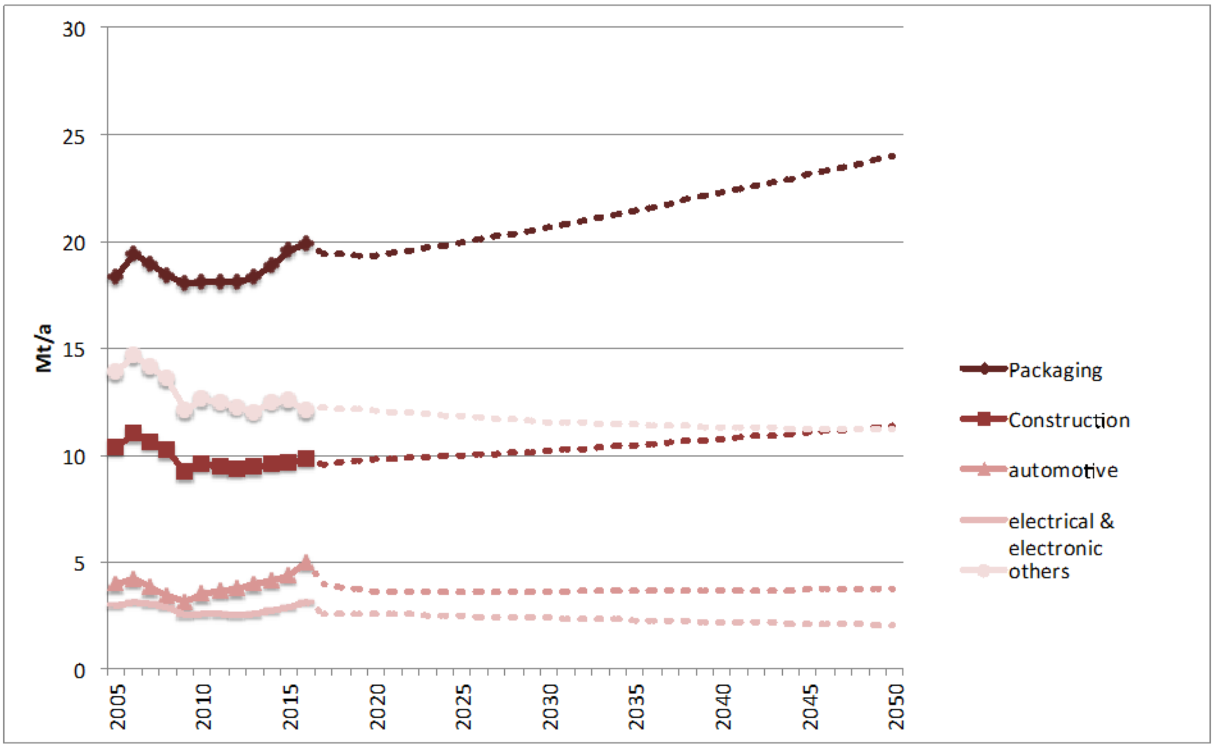


Figure 8. Projection plastics demand by five different plastic converting branches, Europe (WISEE)

As the plastics demand derivation showed in Figure 8 is a mere trend extrapolation it can be considered as business-as-usual. Plastics demand targeted policies may change the relation between GVA and plastics demand in the future. The extrapolation only considers recent (observed) trends of decoupling in the period of 2005 until 2015.

3.3.2 Production

Upstream

The IMAGE model mostly includes a representation of the upstream supply chain (primary-to-intermediate and intermediate-to-product) using conversion efficiencies (product and intermediate), annualized variable costs, and annualized fixed cost. These data are combined to determine the allocation of energy carriers to the production of product or intermediate (see Figure 9).

WISEE explicitly covers the plastics value chain from the supply of base chemicals like olefins and aromatics via intermediates to polymer production (Figure 10). This figure gives a limited representation of the production chains of plastic sorts covered by the model (8 of 12 products) and the figure does not show the feedbacks from demand (with time lag) via recycling. In WISEE, processes are modelled explicitly using literature values on conversion efficiencies while technology choice is exogenously set based on scenario definition.

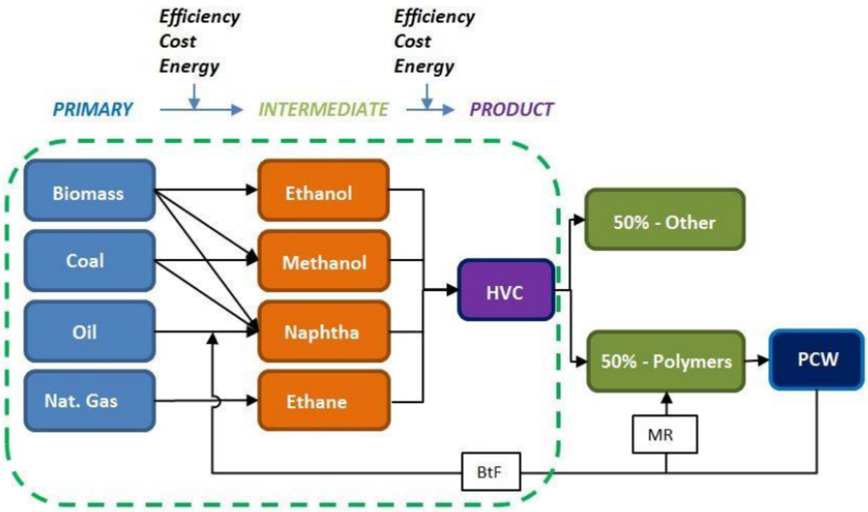


Figure 9. Chemicals supply chain of IMAGE

Source: (Daioglou et al., 2014)

Dynamics in the WISEE plastics module result from stock reinvestment at the beginning of the value chain (olefins and aromatics supply). Feedstock input and technology use is also dependent on the development of recycling. Like in the steel module, expiry of lifetime of existing stocks opens up the window for technological change. Lifetimes of steam crackers and refinery production stock are however significantly longer (40-50 years) than in the steel industry, where at least blast furnaces need a major retrofit after 20-25 years of operation time. So mothballing of stock before expiry of lifetime may be an even more relevant strategy than in the steel industry.

WISEE includes a comprehensive energy, feedstock and carbon stock balance specifically for the plastics sector, showing also the CO_2 effects of waste treatment. WISEE also allows analysing feedbacks with transport fuel supply and spatial analyses. Moreover, WISEE accounts for integrated production (exchange of heat, fuels or hydrogen between different processes at one site).

In WISEE, the plastics upstream covers the following steps:

- crude oil refining
- syngas supply by
    - Steam Reforming
    - Water electrolysis
    - Reverse water gas shift reaction
    - Biomass gasification
    - Waste gasification
- Methanol production
- Steam supply

For information on technologies used in the chemical industry, both IMAGE and WISEE use Ren (2009). IMAGE also used Saygin (2012) and WISEE JRC (2017) and IEA (2009).

Figure 10. Plastics supply chain of WISEE

Downstream

With regard to the downstream supply chain, in IMAGE recycling is based on assumptions regarding maximum recycling rates, for which 50% is assumed for HVC, 20% for methanol and 30% for refinery products. A distinction is made for mechanical recycling (max 30%) and Back-to-Feedstock (BfT, or chemical) recycling (70%).

In WISEE, recycling rates are product specific (e.g. very high for polyolefins from packaging, low for PVC. Backflows from mechanical recycling is limited by limitations in recycled use in products (surplus recycled products are exported to growing markets outside the EU and thus “leave” the system). For some rather complex plastic sorts, monomer recycling (e.g. pyrolysis) is considered (PVC, polyamide).

All other waste collected within the EU may be sent to feedstock recycling (i.e. gasification), depending on collection rates. Today, there are high losses in the system due to net exports of plastics, net exports of plastics in goods (e.g. cars), and litter (waste not collected). These offsets are extrapolated to the future.

Waste incineration is included in both IMAGE and WISEE, allowing some energy recovery that lowers the electricity demand of the non-energy sector. Energy recovery occurs with a thermal efficiency of 30% (increasing to 40% over time) in both models. Embedded carbon is assumed to remain accumulated unless incinerated; therefore, emissions in IMAGE and WISEE are mostly processing emissions and some emissions from incineration. Table 3 gives a complete overview of technologies used in the chemicals/plastics sector of WISEE and IMAGE.

Table 3. Production technologies of the chemical/plastics sector in IMAGE and WISEE

Technology	IMAGE	WISEE
Production routes (site-specific for WISEE):		
Steam cracking	X	X
Steam cracking + CCS		X
Haber-Bosch process	X	X
Back-to-feedstock (Naphtha)	X	
Mechanical recycling	X	X
Intermediates production and polymerisation (standard and best available technologies respectively)		X
Fluidized-bed catalytic cracking (FCC) (+CCS)		X
Fluidized-bed catalytic cracking (FCC) (+CCS)		X
Catalytic reforming		X
Methanol-to-olefins		X
Methanol-to-aromatics		X
Monomer recycling (to intermediates)		X
Platform product to polymer process chains for 13 polymers		X
Feedstock production:		
Distillation crude oil	X	(X)
Naphtha	X	(X)
Methanol	X	X
Ethanol	X	
Ethane	X	
Steam Reforming		X
Water Electrolysis		X
Feedstock recycling (to syngas)		X
Reversed water-gas-shift (CO2 to CO)		X
Steam Reforming (+CCS)		X
Black liquor gasification		X
Utilities:		
steam supply by natural gas boilers		X
steam supply by electrode boilers		X

3.4 Paper and pulp industry

Here the key characteristics of how paper and pulp demand and production is modelled are summarized; more detailed information can be found in Roorda (2006) for IMAGE.

3.4.1 Material and energy demand

In the IMAGE model, the demand for pulp and paper products is based on a relation in historical consumption per capita data and GDP per capita. A logistic growth curve is fitted on the historical production data on total pulp and paper production as found in FAOSTAT (1971-2003) (see Figure 11). By combining this curve with long-term population and GDP projections, which are exogenous trends to the IMAGE model, it provides an (static) estimate for total pulp and paper production that can be extended into the future. In a subsequent step, various pulp and paper products are distinguished by utilizing fixed shares to derive a representation for e.g. mechanical pulp, chemical pulp and recovered paper, as well as newsprint, writing and printing and other paper and paperboard products. To account for some decoupling of the relation between income and demand for product (Järvinen et al., 2012), the IMAGE model includes a time-dependency factor (representing developments such as digitalisation) to curtail the growth with rising income. The rate of curtailment is an extrapolation of the found decline in product demand per capita during the last decade for each paper product (2000-2015), distinguishing between OECD and non-OECD developments.

The demand of WISEE is based on IMAGE.

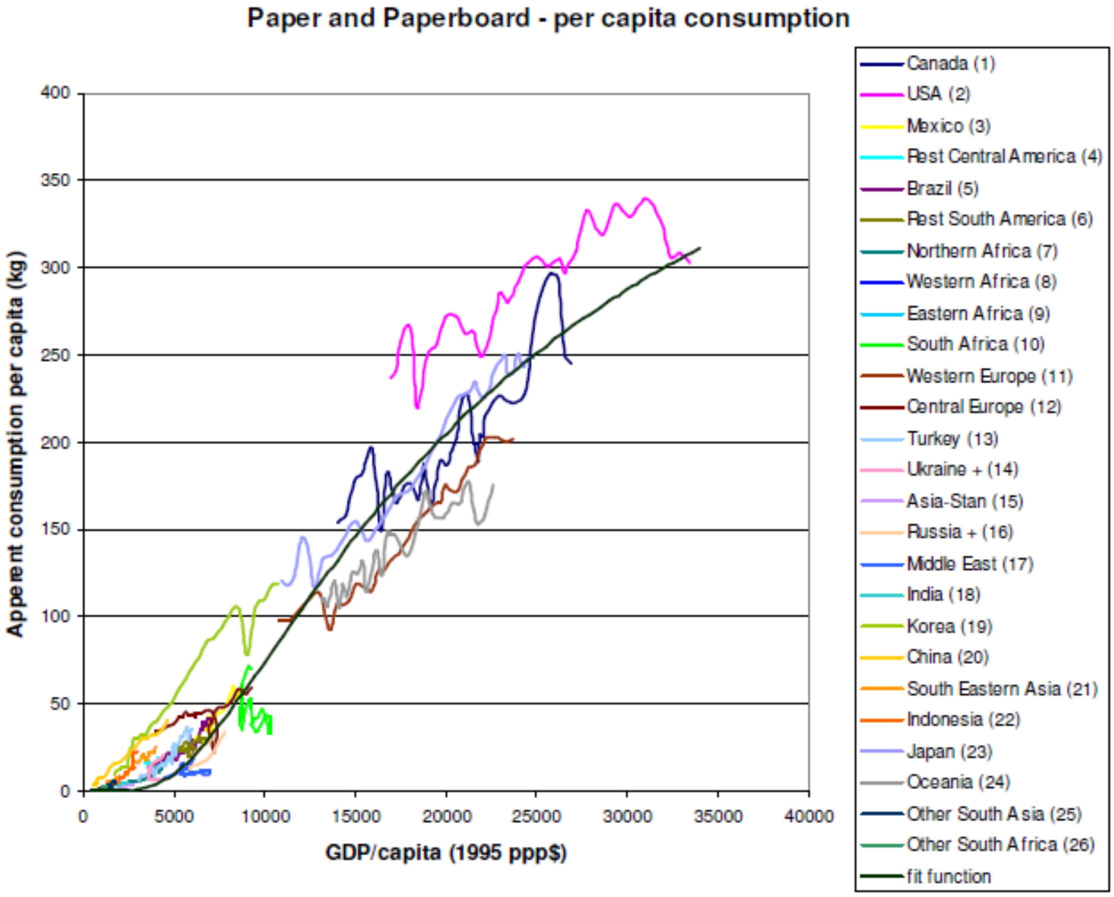


Figure 11. Demand curve for total paper and paperboard in the IMAGE model, prior to curtailing growth
Source: Roorda (2006)

Total energy demand for pulp and paper production in the IMAGE model is derived by multiplying the estimated physical production volumes with specific energy consumption values and time-dependent efficiency improvement factors as reported in VLEEM (2005). A further breakdown of energy demand across the included production technologies and energy carriers is described in the next section.

3.4.2 Production

The IMAGE model includes a simple representation of the pulp and paper industry (Figure 12). The model is focused on common processes in both the pulping and paper making process. As the drying and dewatering processes are the most energy-intensive processes in both the pulping and papermaking industries (GL, 2015c), thermal energy demand is considered the most important aspect of the model. Market pulp is considered the only intermediate product (implying that pulp production happens separately from paper). Furthermore, secondary fibres (repulping processes) are integrated in paper production and processes are assumed to be fully on-line (continuous). All chemical pulping is considered to be following the Kraft method. The Kraft process recovers biomass residues (black liquor) via the chemical extraction of lignin from woody material, which is used as a (bio)fuel in the recovery boiler.

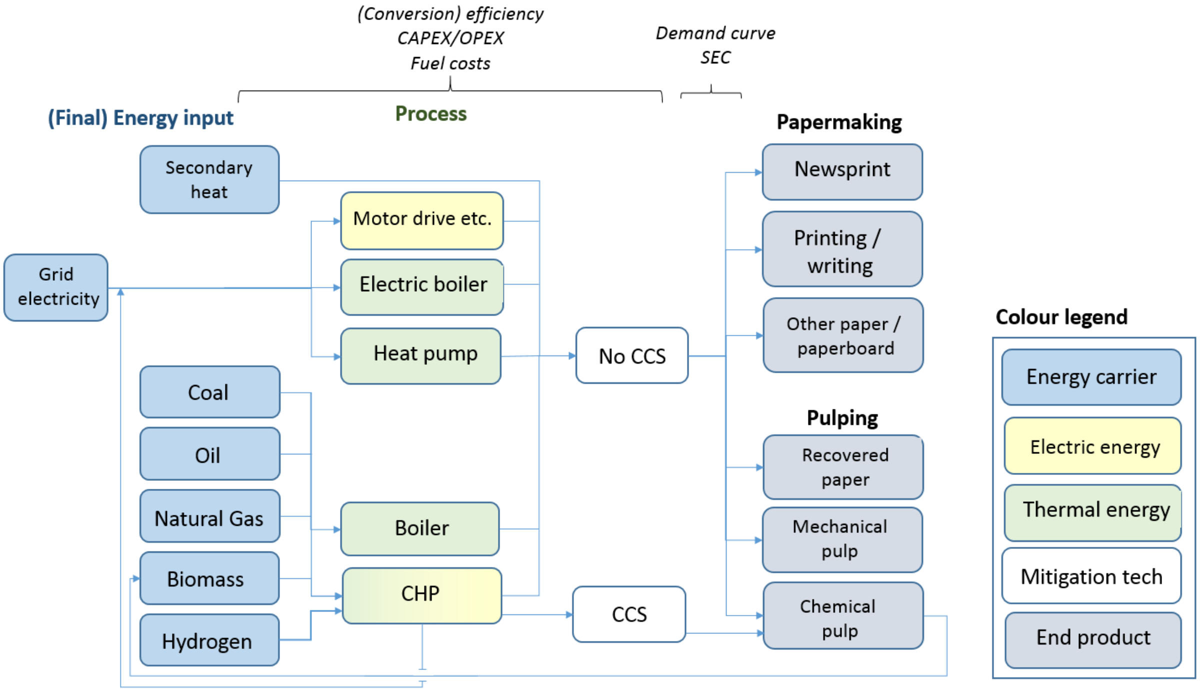


Figure 12. Conceptual overview of the IMAGE pulp and paper industry module

The IMAGE model includes a capital stock model for the on-site thermal energy producing technologies in the pulp and papermaking industry. Various options for thermal energy supply are included (Table 4). It is assumed that 25% of the energy demand can be provided by low-heat technologies, based on Naegler et al. (2015). Thermal energy is considered to be solely destined for (conventional) drying processes, such as contact and steam drying techniques. Electricity is assumed to be used for both mechanical processing of pulp and paper (motor drive, etc.) and (innovative) dewatering and drying techniques. The IMAGE model contains an electricity sector representation that simulates investments and production of electricity for the different end-use sectors. Some of the thermal production options also produce electricity (combined heat and power technologies). This electricity is assumed to be consumed in the sector itself and is therefore not included in the net electricity consumption of the sector.

The WISEE model also includes on-site thermal steam and electricity generation technologies for different processes in the pulp and paper industry like pulping, bleaching, fibre recovering and paper machines for different paper and paperboard grades (Figure 13). Power-to-Heat is one important electrification strategy in a circular economy, it includes electrode boilers as well as conventional low-temperature and innovative high-temperature heat pumps.

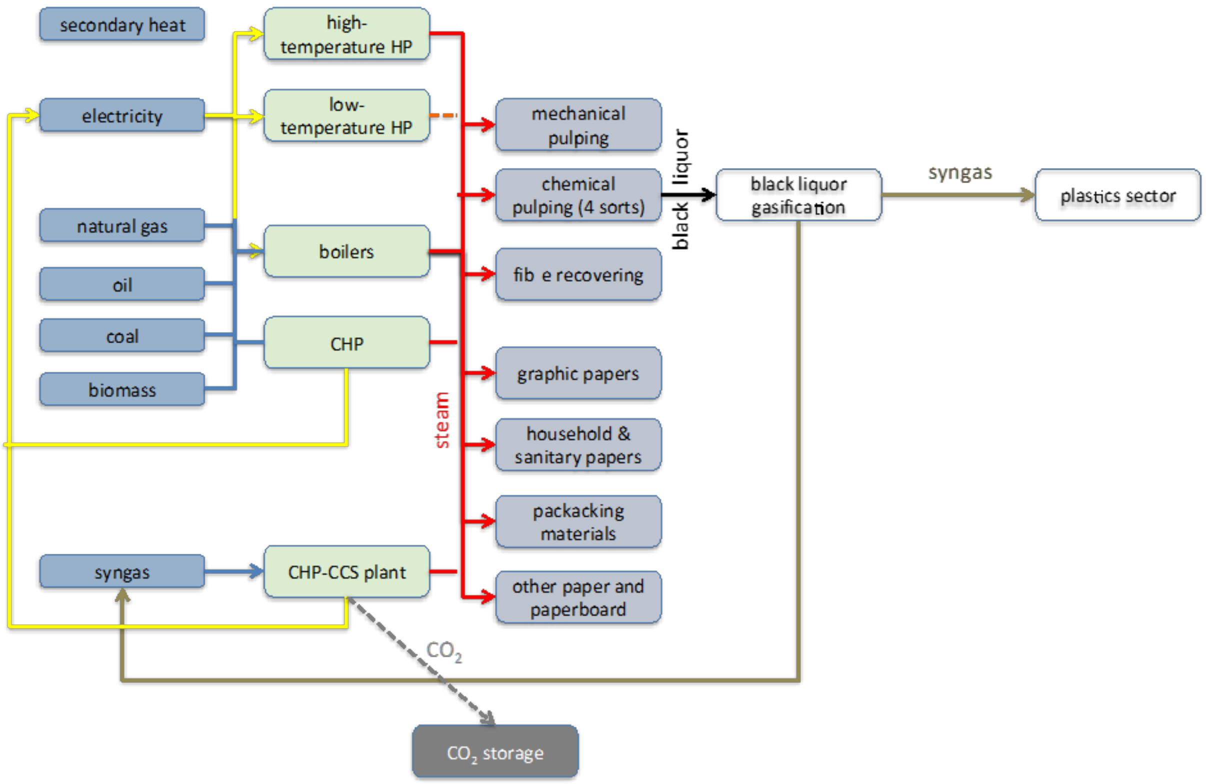


Figure 13. Conceptual overview of the WISEE pulp and paper industry module

Several other options for decarbonisation in the pulping industry are reported in literature, such as carbon capture and storage (CCS) in the Kraft process (the dominant process used in chemical pulping) (Onarheim et al., 2017). Both IMAGE and WISEE include the option to add CCS to boilers in chemical pulp production. WISEE only includes CCS at black liquor gasification plants in the chemical pulp production and the downstream syngas combustion in a CHP process whereas IMAGE also includes CCS retrofit at existing boilers and CHP plants. The use of biomass in combination with CCS implies that the pulping industry can deliver negative emissions.

In IMAGE, process and technology information of the paper and pulp sector is taken from Große et al. (2017), Onarheim et al. (2017), and Naegler et al. (2015). WISEE uses data of Rehfeldt et al. (2018), JRC (2015), (Fleiter et al., 2012b) and Grigoray (2009).

Table 4. Production technologies of the paper and pulp sector in IMAGE and WISEE

Technology	IMAGE	WISEE
Pulp and paper:		
Pulp production		X
Paper machines		X
Paper recycling		X
Steam supply:		
Electric boiler	X	X
Electric heat pump	X	X
Secondary heat	X	X
CHP hydrogen	X	
CHP coal	X	X
CHP coal + CCS	X	
CHP oil	X	X
CHP oil + CCS	X	
CHP natural gas	X	X
CHP natural gas + CCS	X	
CHP biomass	X	X
CHP biomass + CCS	X	
Boiler coal	X	
Boiler oil	X	
Boiler natural gas	X	X
Boiler biomass	X	X
Boiler biomass + CCS	X	
Black liquor gasification and use in combined cycle		X

3.5 Meat and dairy

The IMAGE model includes a simple representation of the food processing sector. The model builds on earlier work on agriculture (Stehfest et al., 2014) and food demand (Bijl et al., 2017). Here the key characteristics of the meat and dairy sector in IMAGE are summarized; more detailed information see the above references. WISEE does not have a process specific representation of the meat and dairy sector, so there will no WISEE results presented in this section.

3.5.1 Material and energy demand

The IMAGE model includes a dynamic food demand model which is, like the other sectors, driven by the key drivers population and income (see Figure 14). The model is based on Engels law, which states that households with lower incomes generally spend a larger share of their income on food (Engel, 1857). The model represents demand for the same 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). Scenarios on dietary change can be modelled by substituting cattle meat by pulses and soy or by reducing expenditures on food in specific households.

Total energy demand for food processing in the IMAGE model is derived from multiplying the total physical production volumes with specific energy consumption values as reported in Ramirez Ramirez (2005) and Wang (2014). A further breakdown of energy demand across the included production technologies and energy carriers is described in the next section.

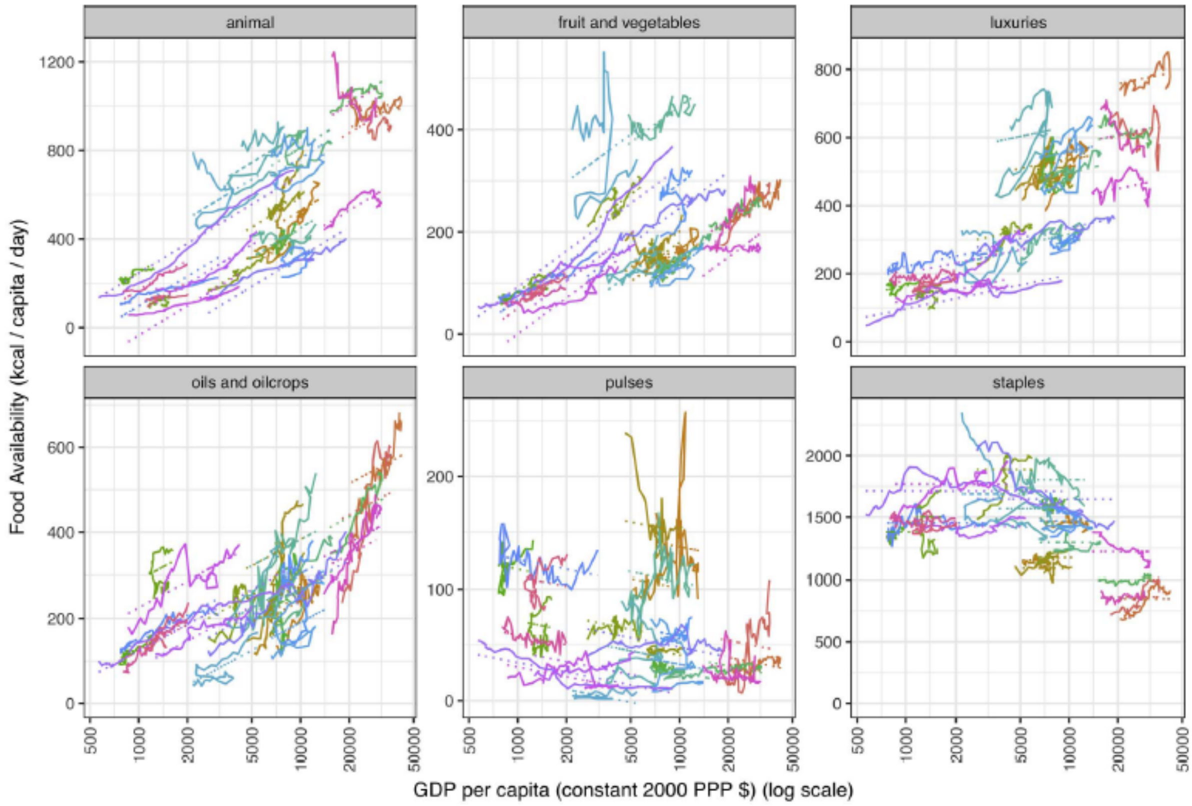


Figure 14. Demand curves for food products aggregated to 6 main categories (IMAGE)

Source: Bijl et al. (2017). Colours represent all 26 world regions in the IMAGE model

3.5.2 Production

The IMAGE model includes a capital stock model for the following on-site thermal energy producing technologies in the food processing industry (technology representations based on Große et al. (2017):

- Electric boiler
- Electric heat pump
- Secondary heat
- CHP hydrogen
- CHP coal
- CHP oil
- CHP natural gas
- CHP biomass
- Boiler coal
- Boiler oil
- Boiler natural gas
- Boiler biomass

The use of heat generating technologies is differentiated for two specific temperature levels (>100°C and <100°C); see Figure 15. Both represent 50% of the total heat demand (Naegler et al., 2015). CHP hydrogen, secondary heat and the electric heat pump are only available for low temperature heat production. Demand for electric energy is supplied via the power sector representation in IMAGE.

Electricity is assumed to be used for both mechanical processing of food products (motor drive, etc.) and cooling.

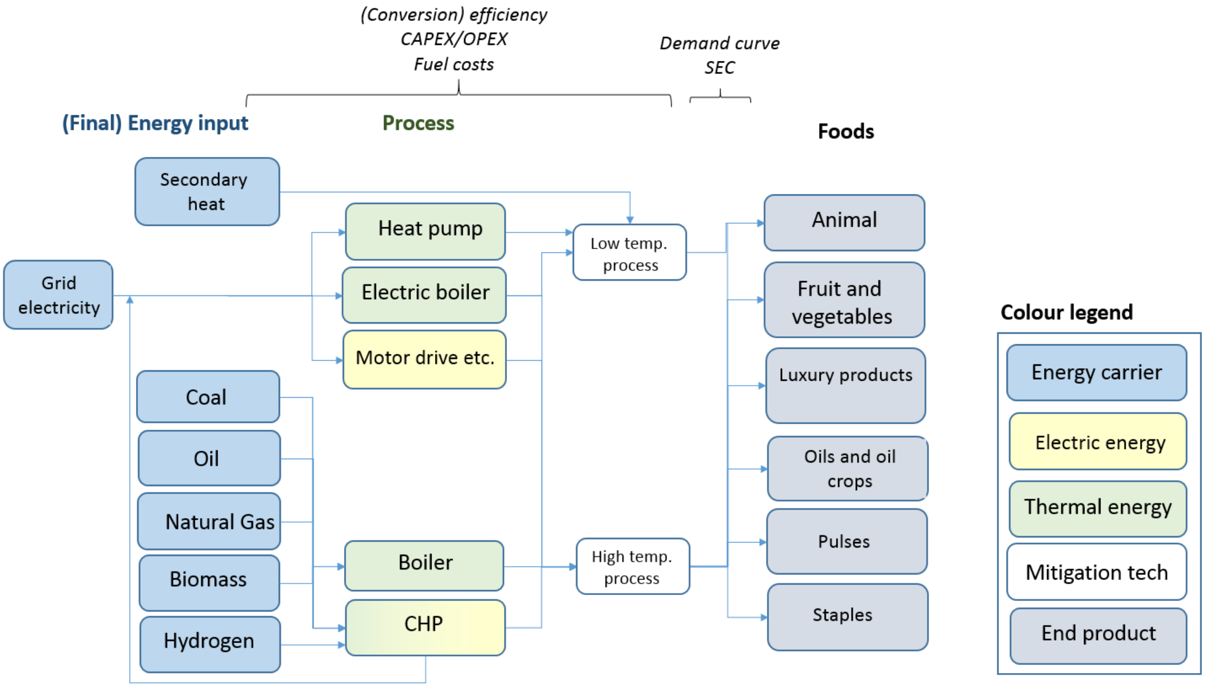


Figure 15. Conceptual overview of the IMAGE food processing industry module.

* The foods represent an aggregated version of the 46 food categories to six main classes.

4 Scenarios

4.1 Trends in population and GDP

Our scenarios are based on socio-economic trends of the shared socio-economic pathway SSP2 (O'Neill et al., 2017). In this pathway, social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Most economies are politically stable. Globally connected markets function imperfectly. Technological development proceeds apace, but without fundamental breakthroughs. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Even though fossil fuel dependency decreases slowly, there is no reluctance to use unconventional fossil resources. These moderate development trends leave the world, on average, facing moderate challenges to mitigation. Overall, SSP2 can be regarded as a middle-of-the-road scenario, with global population reaching 9.2 billion by 2050, of which 760 million in Europe (Figure 16). Relative to 2010 numbers, this implies an increase of 33% globally and of 3% in Europe. Globally, GDP per capita growth rates are about 3% in the short term, declining to 2% by 2040 and about 1.7% mid-century.

The demand for the different products depends on assumptions on population, GDP and structural change. For the pathways developed in this report, the development of these variables are taken from the SSP database (https://tntcat.iiasa.ac.at/SspDb/ and Riahi et al., 2017). The GDP per capita projections in this database are from the OECD (Dellink et al., 2017), while population projections are taken from Kc and Lutz (2017).

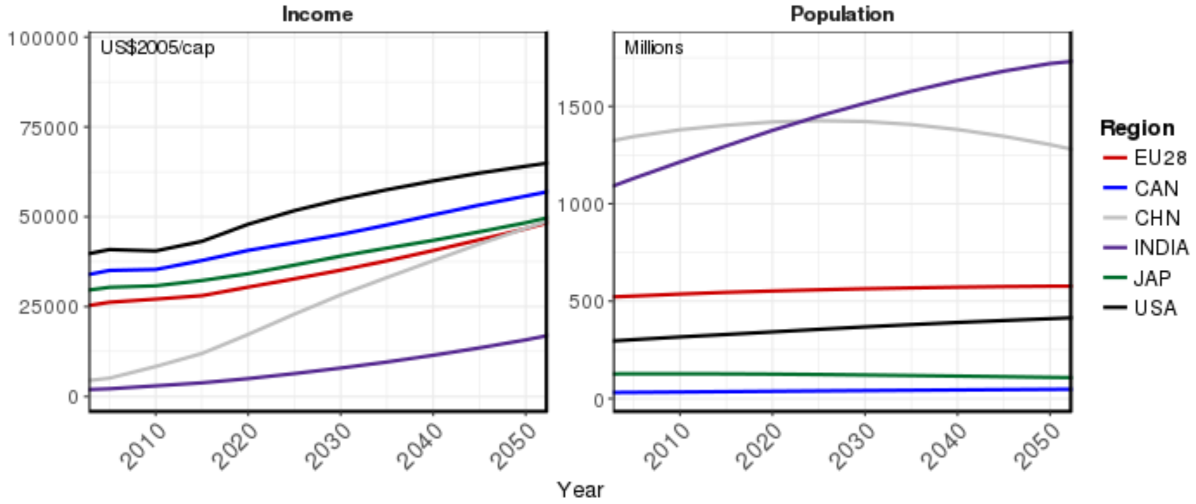


Figure 16. Population and GDP per capita trends in SSP2, Europe vs world regions

4.2 Decarbonisation storylines & interaction

For the global and overall European decarbonisation scenarios developed by IMAGE, we have analysed two different climate goals which were assumed to be achieved cost-effectively across regions, sectors, and over time (see Table 5). In our scenario called *2 Degrees*, a radiative forcing level of 2.6 W/m^2 by the end of the century is targeted. This gives a likely chance of keeping global temperature change below 2 °C. The more stringent *1.5 Degrees* scenario targets a radiative forcing level of 1.9 W/m^2 by the end of the century and gives a more than 50% chance of keeping global temperature change below

1.5 °C. In IMAGE, these respective climate targets are achieved by imposing a continuous and exponentially increasing carbon price on the economy from 2015 and onwards, so that low-carbon investments become more interesting economically. A uniform carbon price is imposed across regions and sectors, which ensures that the climate target is being met cost-optimally. While this may not reflect the most feasible implementation of the Paris climate agreement, it does provide an interesting reference point for policymakers. Where relevant, the decarbonisation scenarios are compared with baseline developments (i.e. developments without imposing a carbon price) to get some insight in the mitigation challenge of the decarbonisation scenarios.

In WISEE, decarbonisation scenarios are implemented differently, as the choices in WISEE are not exclusively based on costs. Instead, scenarios in WISEE are typically built around scenario storylines sharing assumptions on general technology decisions. The WISEE industry modules are operated as stand-alone sector models in REINVENT, which allows for the building of sector specific scenarios (as foreseen in D4.3). Two scenarios have been built (see Table 5): The *CCS scenario* relies on existing assets, which are assumed to be largely equipped with carbon capture (and storage) technology. In contrast, the "circular scenario" (*CIRC* scenario) assumes circularity as the core strategy, which is complemented by a far reaching electrification of energy use. For both scenarios, product demand is taken from IMAGE, except for plastics (for more details, see Section 3.1.1).

Consistency in the WISEE scenario storylines is crucial. For instance, it would not be sensible to assume a broad (economy-wide) application of CCS in combination with the application of power-to-X options in a certain sector. Scenario storyline decisions can be built around the system categorisation as provided by Fischedick et al. (2013), differentiating between resource efficiency, energy efficiency, carbon efficiency, material efficiency, service efficiency and recycling. The CCS scenario focuses on carbon efficiency as an end-of- pipe solution whereas the *CIRC* scenario explicitly includes all strategy elements except material efficiency and service efficiency. The latter two categories are only included as general trends.

Table 5. Main characteristics of scenarios used

Scenario name	Emission or climate target	Storyline	Model	Start year
BL	None	Business as usual	IMAGE	-
2 Degrees	2.6 W/m^2 by 2100	Cost-optimal	IMAGE	2015
1.5 Degrees	1.9 W/m^2 by 2100	Cost-optimal	IMAGE	2015
CCS	Complete decarbonisation of industrial sector	Application of innovative CCS technologies requiring an exchange of assets	WISEE	2015
CIRC	Complete decarbonisation of industrial sector	circularity and electrification as core strategies	WISEE	2015

5 Results

5.1 Broader system changes

The IMAGE model allows an integrated assessment of the effect of decarbonisation ambitions on the broader human and natural system over time. In this chapter, the broader system is addressed first before moving towards the industry sectors individually. We analyse the IMAGE forward-looking perspective to draw out insights on systemic change across Europe. The observed changes are subsequently put into perspective by comparing the European results to the responses as found for various large and emerging economies (the Unites States of America (USA), Canada (CAN), China (CHN), India (INDIA), Brazil (BRA) and Japan (JAP)). These regions are selected for their large contribution to the global market for the REINVENT manufacturing sectors.

5.1.1 Final Energy use

The IMAGE 2 °C (*2 Degrees*) and 1.5 °C (*1.5 Degrees*) scenarios show large changes in the energy system in the coming decades (Figure 17). Although all main economic sectors remain to some degree dependent on fossil fuels in the coming decades, the IMAGE decarbonisation scenarios show clear shifts from oil and gas towards biofuels and electricity in the transport sector, from gas to electricity in the residential and commercial sector, and from coal and gas to electricity and biomass in industry. Under our *1.5 Degrees* scenario, improving energy efficiency plays an even more important role than under our *2 Degrees* scenario, especially in transport and industry. Furthermore, all sectors show a stronger electrification rate under our *1.5 Degrees* scenario.

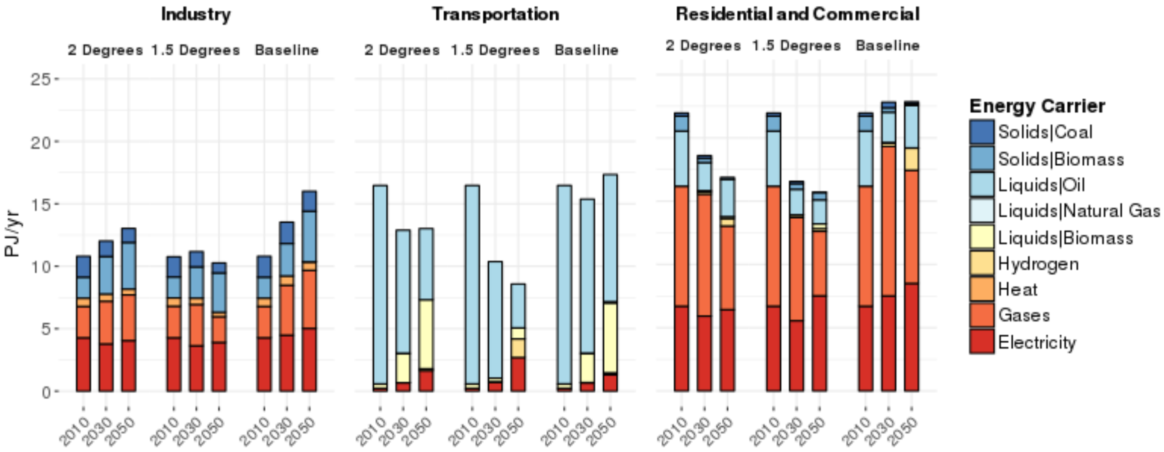


Figure 17. System transformations for the main economic sectors in EU28 in the 2 °C and 1.5 °C scenario

5.1.2 Power supply

The scenarios show that Europe decarbonises the power sector via adoption of solar and wind in the near term, while biomass with CCS starts entering the system from about 2030 onwards, especially in the *1.5 Degrees* scenario. Nuclear energy is almost phased out completely in Europe by 2050 in both the baseline and mitigation scenarios, as cheaper options are available (solar and wind in all scenarios, and in addition coal and gas in the baseline).

As both Europe and the world as a whole rely strongly on electrification to decarbonise the economy, the demand for electricity is higher in the *1.5 Degrees* scenario than in the *2 Degrees* scenario.

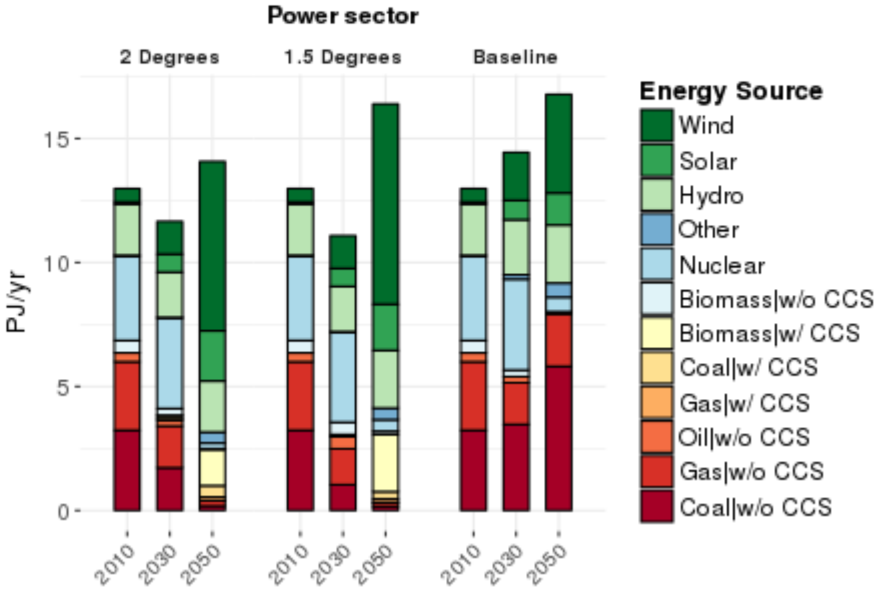


Figure 18. Projected fuels and technologies for power production, Europe (IMAGE)

5.1.3 CO_2 emissions

The *2 Degrees* scenario shows a complete decarbonisation of the power sector before 2050. As a result of the larger BECCS use in the rest of the world, especially in Canada and India, a complete decarbonisation of the power sector takes place earlier in the rest of the world than in Europe (note that this is under the assumption of cost-optimal reduction across regions, neglecting any equity considerations). However, in Europe CO_2 emissions decline faster in the near term than most other regions in both mitigation scenarios due to the faster increase of renewables. The negative emissions in the electricity sector more than completely offsets remaining emissions in the energy demand sectors by 2050 in our *1.5 Degrees* scenario.

The difference in emissions between the *2 Degrees* and *1.5 Degrees* scenario is especially large in industry, which is due to less energy use and a stronger electrification (see also Figure 17). In Europe, net CO_2 emissions are very close to zero already around 2035 in the *1.5 Degrees* scenario, whereas in the *2 Degrees* scenario, they remain substantial until at least mid-century.

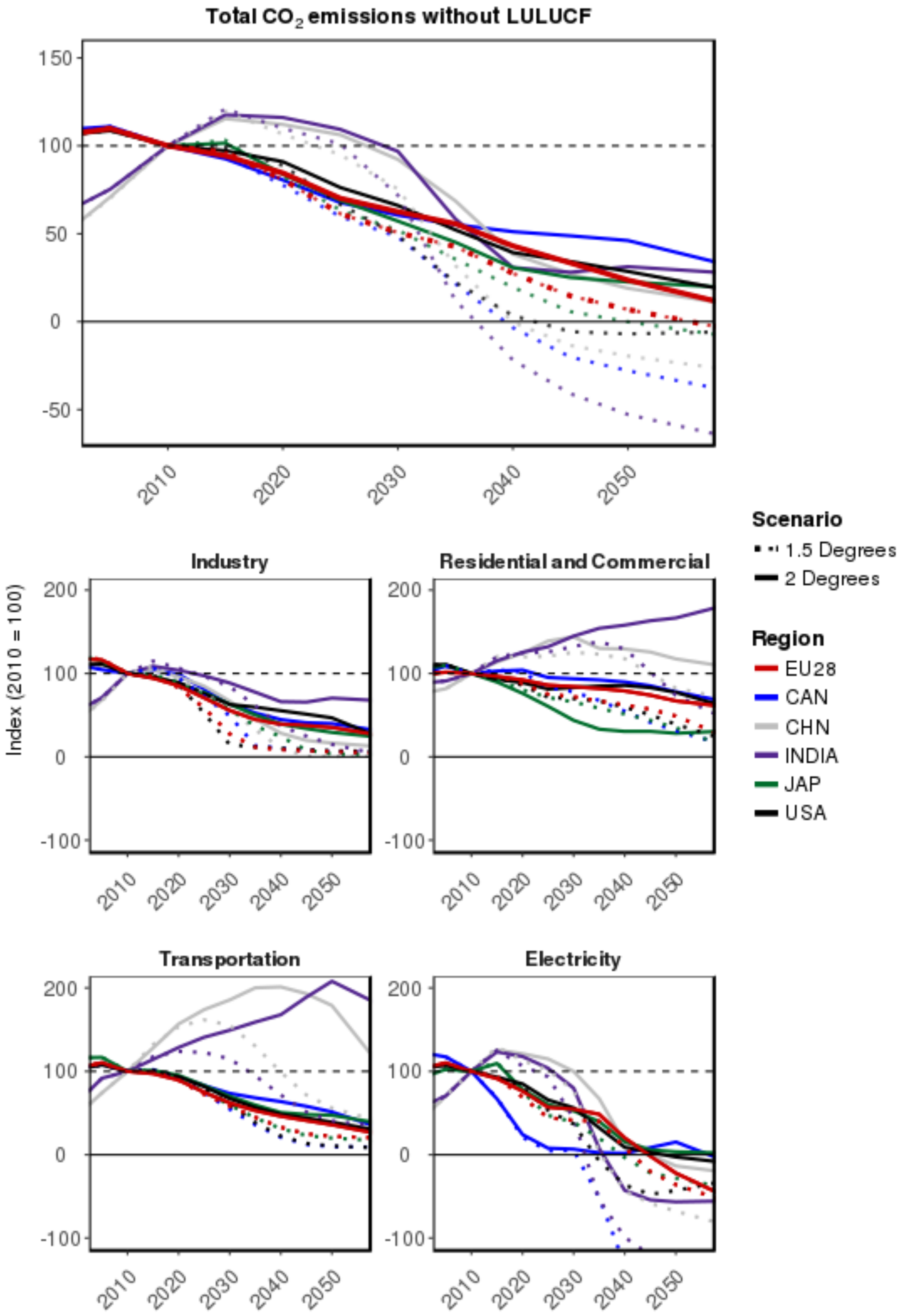


Figure 19. Projected CO_2 emissions for main economic sectors, Europe vs other world regions (IMAGE)

5.1.4 Carbon capture and storage

The extent and way in which carbon is captured and stored is dependent on the stringency of the climate objective (see Figure 20). Until 2030, hardly any CCS is adopted. By 2050, the total amount of CO_2 captured is significant, with more CO_2 captured in the *1.5 Degrees* scenario relative to the *2 Degrees* scenario. However, less CO_2 is captured in fossil power plants as CCS is mainly applied in combination with biomass to decrease emissions even further. Interestingly, only in our *1.5 Degrees* scenario it becomes interesting for industry (and particularly the pulping sector) to adopt carbon capture and storage in bio-based thermal energy supply.

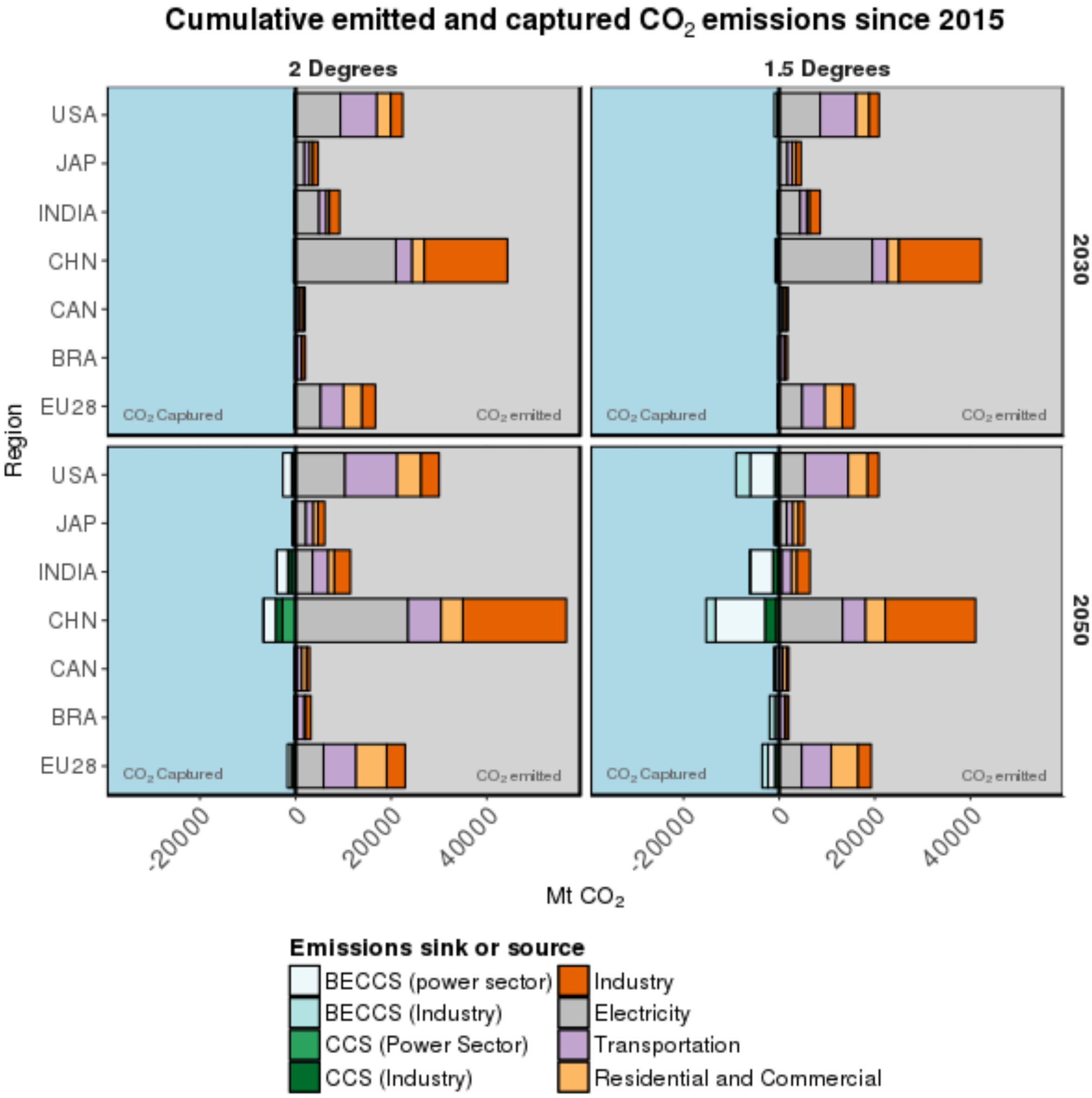


Figure 20. Cumulatively emitted and captured CO_2 emissions across various large and emerging economies since 2010.

5.2 Decarbonisation pathways for industry

In this section the industry sector as a whole and the separate manufacturing industries (steel, plastics, paper and pulp, and meat and dairy) are analysed in more detail. The development of these industries are analysed by both the IMAGE model and the WISEE model. The IMAGE model is devised to compare the response of the European industry on the aggregate level to the broader global context. More detailed technological and spatial system transformations are analysed with the WISEE model.

5.2.1 Industry sector

Total industrial energy use stays relatively constant in the *2 Degrees* scenario, both in Europe as globally (see Figure 21). Compared to baseline energy demand, this implies a substantial reduction (20% by 2050). The *1.5 Degrees* scenario shows a continuous decline in energy demand in Europe, which approaches a 40% demand reduction compared to the baseline by 2050. The reduction in energy demand in the *1.5 Degrees* scenario is less drastic globally.

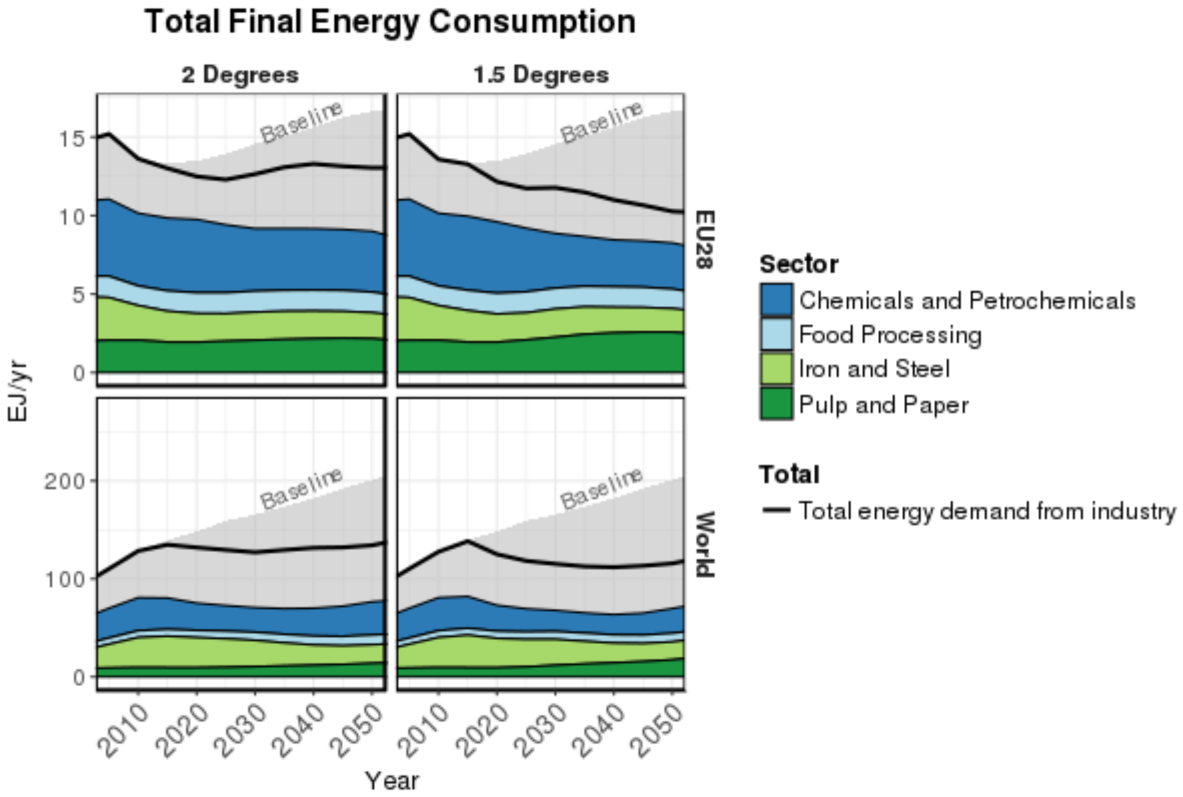


Figure 21. Projected final energy demand by manufacturing industry (IMAGE)

In the *2 Degrees* scenario, European industrial CO_2 emissions are about 60% lower by 2050 than today, while in the *1.5 Degrees* scenario a complete decarbonisation takes place (Figure 22). The latter is predominantly a result of negative emissions adopted in the pulping and paper industry (see Figure 23 and Section 5.2.4). Similar trends are found globally.

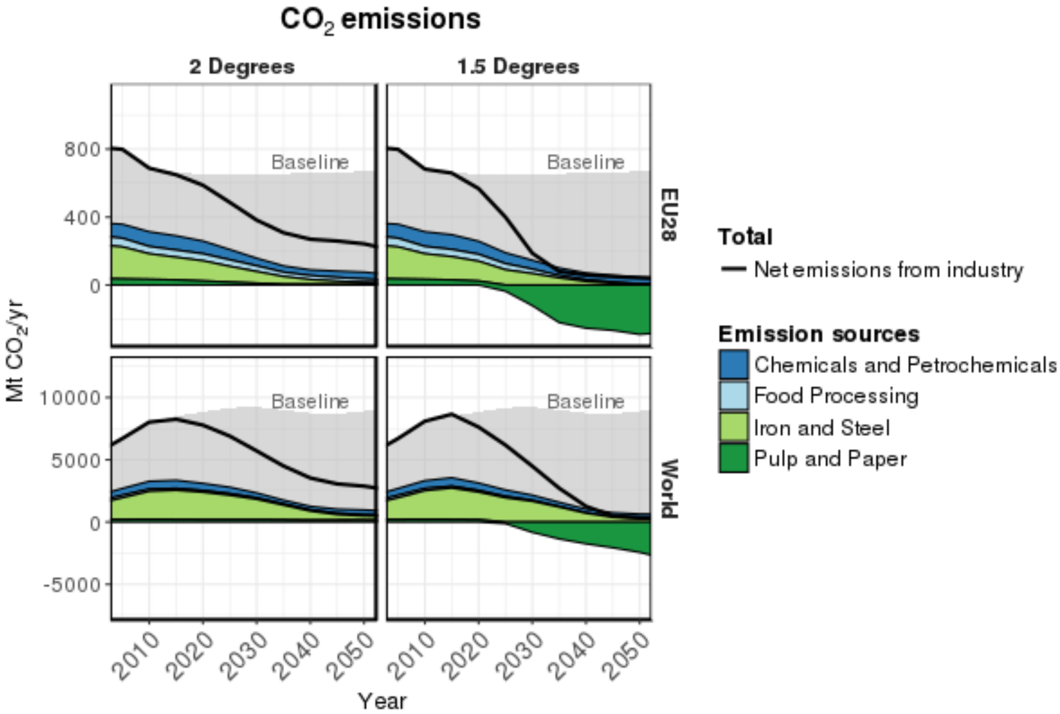


Figure 22. Projected net CO_2 emissions for specific manufacturing industries (IMAGE)

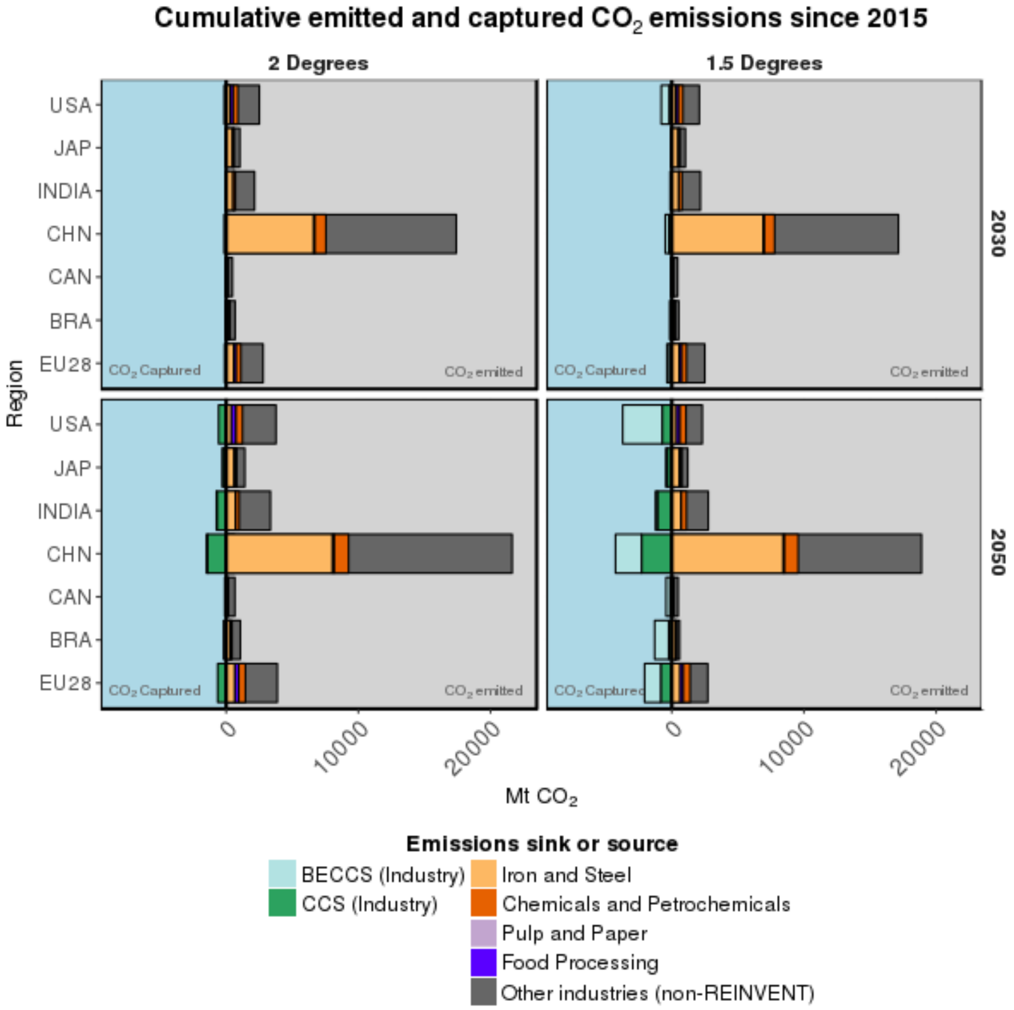


Figure 23. Projected captured and emitted industrial CO_2 emissions, Europe vs other world regions (IMAGE)

5.2.2 Steel

5.2.2.1 Global vs European trends

European production levels for crude steel are projected to stay relatively constant (Figure 24). Global demand is increasing, but is projected to stabilize after 2020. However, as more scrap is projected to become available, steel production from scrap is projected to increase strongly globally. In Europe, this increase is much less pronounced.

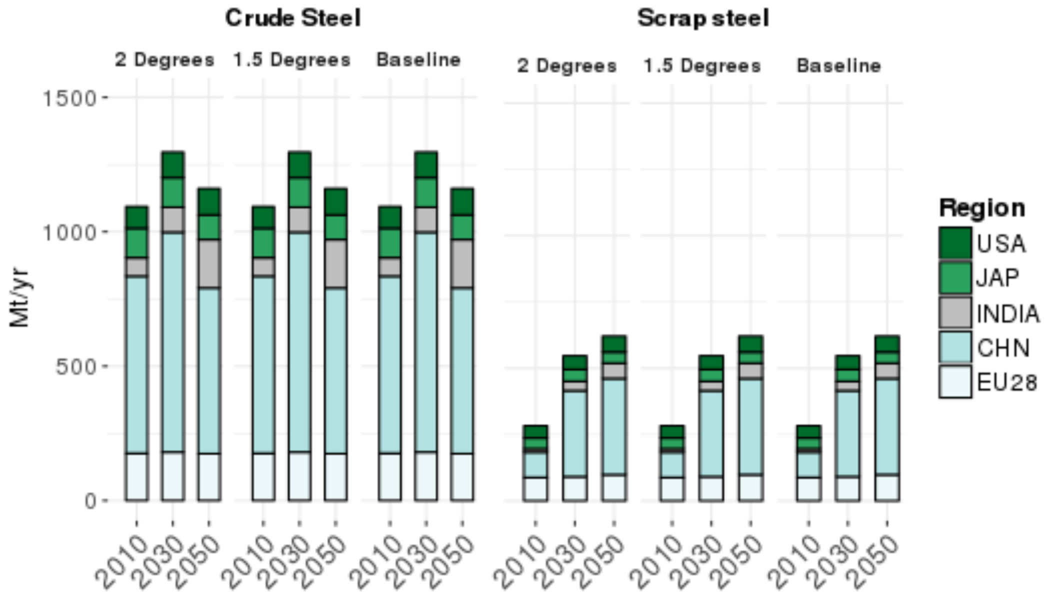


Figure 24. Projected iron and steel production volumes (IMAGE)

The energy intensity of the European steel industry is currently much lower than the global average (Figure 25). In our scenario, the global average energy intensity improves towards the EU level, which only shows incremental improvements. As European production volumes remain relatively constant, total energy use of the European steel sector stays relatively constant as well.

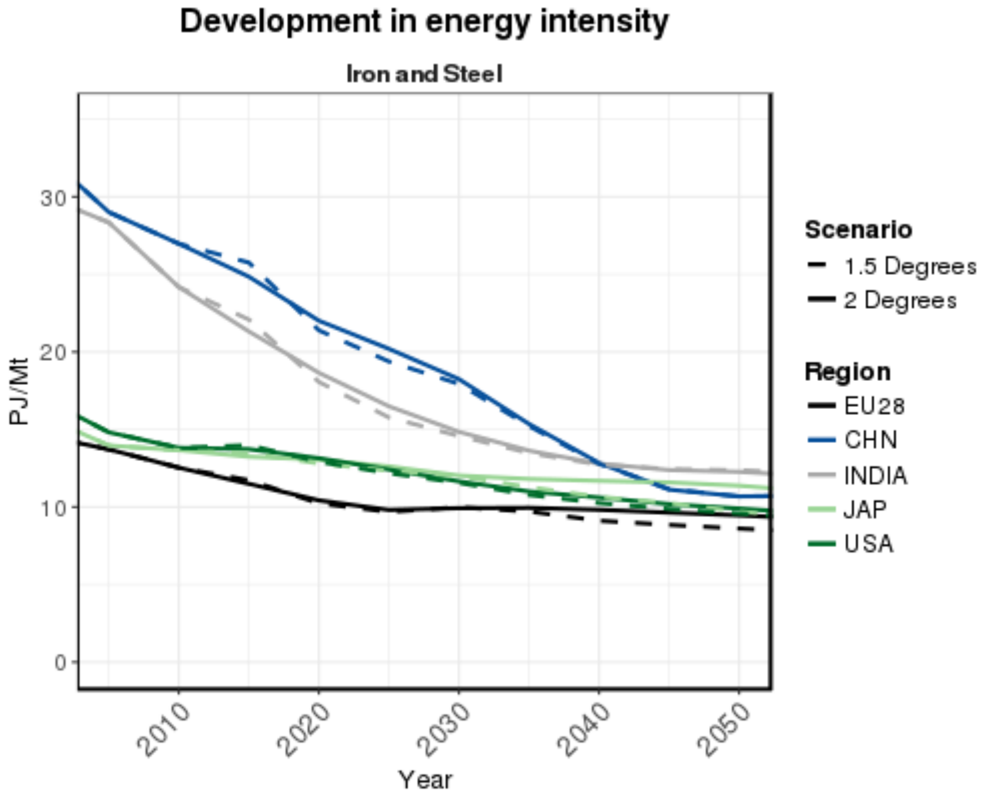


Figure 25. Projected energy intensity for crude steel production (IMAGE)

The type of energy used only shows incremental changes over time (Figure 26). Currently, the iron and steel sector is largely coal-based. While coal is being replaced by electricity and modern biofuels, this happens only very slowly. Therefore, by 2050, coal is still the main energy carrier by far. In IMAGE, large-scale adoption of alternative low-carbon technologies are projected not be economically viable by 2050, even with the carbon prices applied in the model. Therefore, CCS is the main technology used in the steel sector to decrease emissions from the current 180 $MtCO_2$ to about 40 $MtCO_2$ in the decarbonisation scenarios (Figure 27).

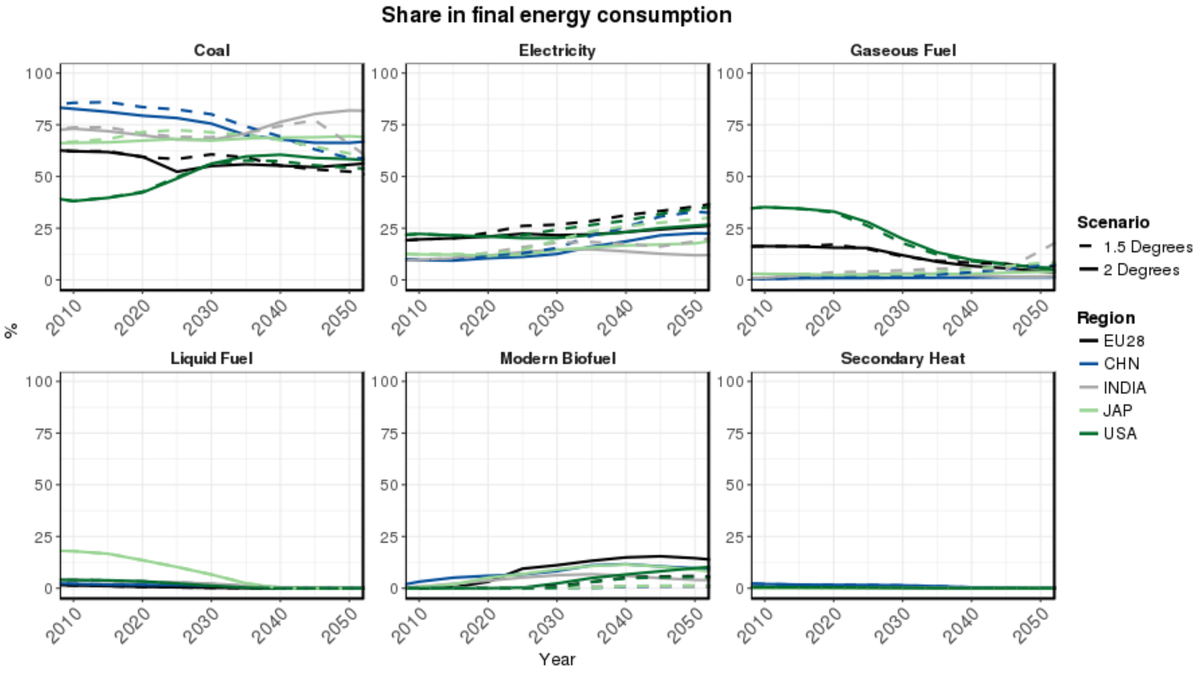


Figure 26. Projected shares of energy carriers in total final energy consumption for the iron and steel sector in Europe (IMAGE)

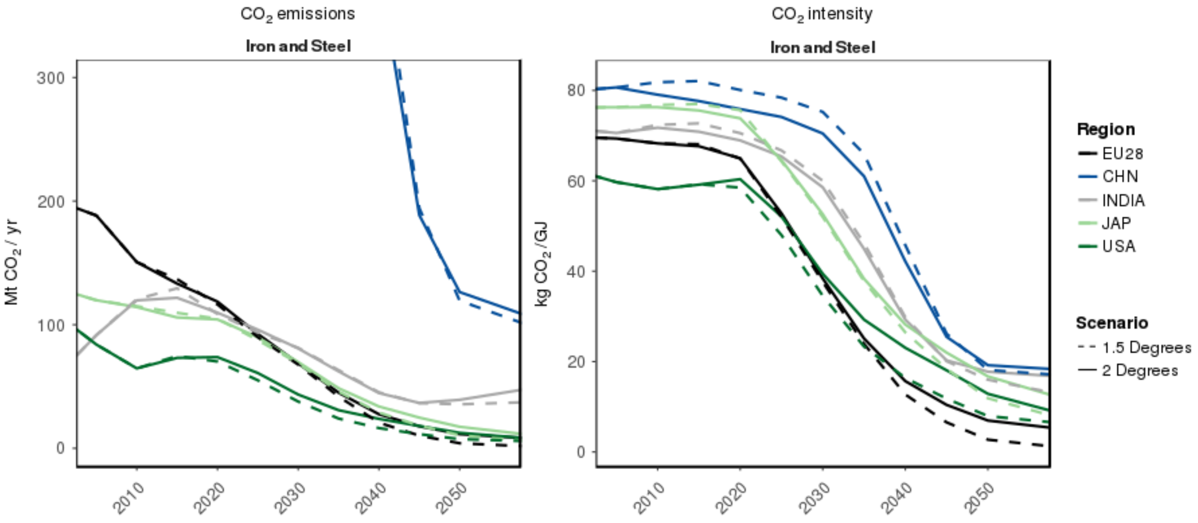


Figure 27. Projected CO_2 emissions and CO_2 intensity of the iron and steel sector, Europe vs other world regions (IMAGE)

5.2.2.2 European technology pathways

In the EU28 – like worldwide – there is currently an excess capacity for steel making. In the base year 2015 the primary route was utilised by 80% and EAF steel mills by only 67%. The production pathway according to the IMAGE projection foresees some recovery of the steel market and a shift to the secondary steel (EAF) route in the mid and long term. However, both routes melt down capacities until 2030 in the two WISEE scenarios: The BF/BOF route loses 6% compared to 2015 (recent closures are regarded) and capacities of the EAF route in the EU are lowered by 19%. The phase-in of low carbon breakthrough technologies begins after 2030. From then on regulators do not accept any refurbishment of conventional primary production stock anymore according to the scenario storylines. In the *CIRC* scenario, hydrogen is introduced as a reducing agent for the production of direct reduced iron, which can be processed to steel in a blast oxygen furnace (BOF) or an EAF (Figure 28). In the CCS scenario, smelt reduction with CCS is introduced as a new best-available technology from 2030 on and replaces the existing blast furnace route (incl. the coke ovens and sinter plants).

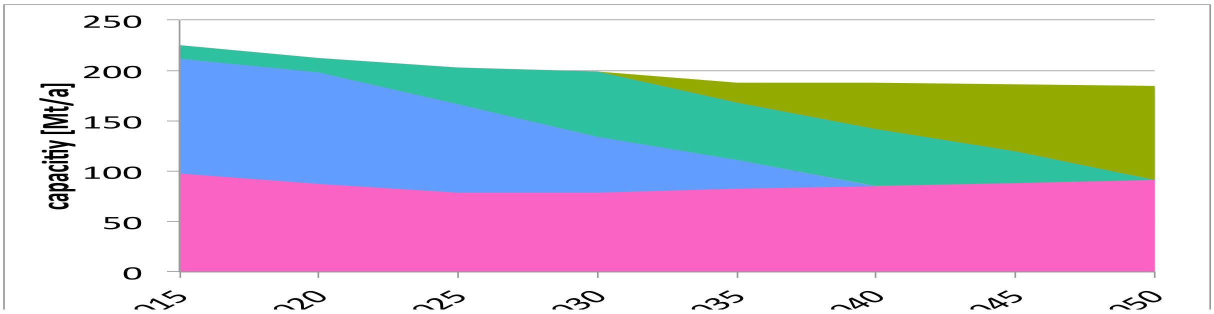


Figure 28. Projected technologies in steel making (WISEE)

Figure 29 shows the phasing out of blast furnace capacities by country. The type of technology used as replacement of blast furnace depends on the scenario and location. Replacement options in the *CIRC* scenario are:

- Replacing a BF at an existing steel mill by a DRI plant using hydrogen produced at the site from the local electricity grid.
- Replacing a BF at an existing steel mill by a DRI plant using imported hydrogen.
- Import DRI from sweet spots within the EU-28 (e.g. Sweden) or from abroad (Brazil, Middle East, Australia).
- Import crude steel from sweet spots within the EU-28 (Sweden) or from abroad (Brazil, Middle East, Australia).

Replacement options in the CCS scenario are:

- Replacing a BF (+sinter plant and coke oven) at an existing steel mill by a smelt reduction plant and connect the site by a CO_2 pipeline to a CO_2 storage site.
- Remove crude steel production to a new site nearer at a storage.

The latter case might be not the most economic efficient one, as CO_2 transport via pipeline is relatively cheap in comparison to a greenfield steel mill investment, but as inland CO_2 pipelines are less accepted by the public, primary steel production could still move to the coast.

Figure 29. Projected capacity change in blast furnaces, EU countries (WISEE)

Figure 30 displays the primary energy use by production technology of the iron & steel sector. It shows that there is an efficiency gain in the primary route due to reinvestments of best available technologies in the regular investment cycle. In spite of an increase in production volumes, coal use declines. Moreover, a more efficient gas recycling (especially at BOF stocks) is projected. Due to efficiency improvements in the hot rolling mills at the integrated steel plants, the excess gas availability at steel sites increases, leading to an increased electricity production from coke oven gas, blast furnace gas and BOF gas. The secondary steel route increases its share in the mid and long term in both scenarios and becomes also more efficient. Hydrogen replaces coal from 2030 onwards and the steel gas diminish in the *CIRC* scenario because of the shrinking role of the BF/BOF route.

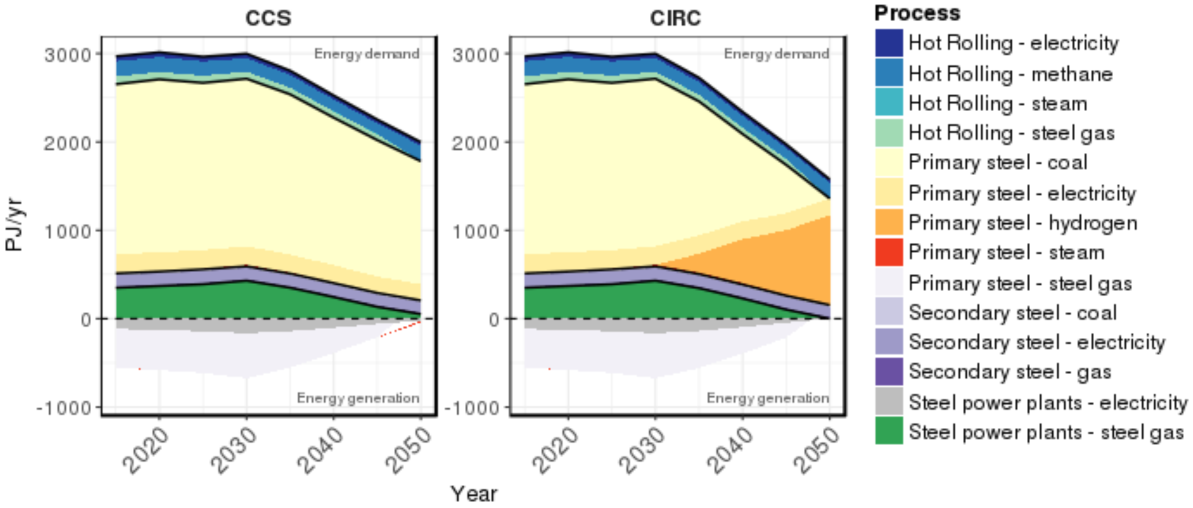


Figure 30. Projected primary energy use by production technology in the iron & steel sector, Europe (WISEE)

Up to 2030, the *CIRC* and CCS scenario do not differ. However, upfront investments in a CO_2 infrastructure are made at least from 2025 onwards (and demonstrators have to be built before). Coal is more efficiently used in the smelt reduction route than in the BOF route, so there is no gas surplus to be used in the power plants. Together with a reduction in primary steel production by 16% by 2050, this results in a slowly shrinking coal demand in the CCS scenario.

The two WISEE scenarios do not differ with regard to hot rolling: Energy efficiency improves over the years, the steel gas use as an energy carrier in the integrated steel mills phases out and through recuperative burners excess steam generation can be minimized.

Direct CO_2 emissions are mostly due to coal and coke use in primary steel making. Direct CO_2 emissions decrease from 2020 on, but slowly (Figure 31; which includes emissions from electricity generation fuelled by coal-derived steel gases). Only from 2030, when stock exchange begins, the emissions decline significantly. In the hot rolling sector decarbonisation is reached by a substitution of natural gas by bio-methane.

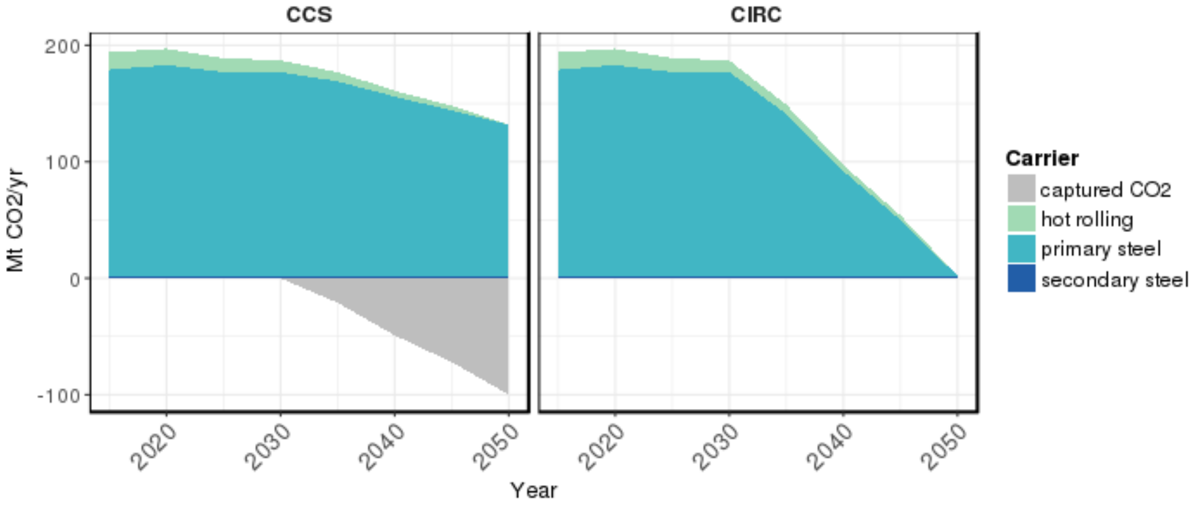


Figure 31. Projected CO_2 emissions in the iron & steel sector (WISEE)

*) Primary steel incl. steel gas use in power plants

Figure 32 shows that CO_2 emissions of the two IMAGE scenarios differ only a little, which is an indication that the additional emission cuts required in the 1.5 Degree scenario are achieved in other sectors. The two WISEE pathways perform in the mid-term more like the IMAGE baseline, which is not too surprising, as WISEE follows a simulation approach rather than an optimisation approach. The IMAGE model however identifies rapid reductions as an optimal pathway to achieve a lower level of total cumulated emissions. This requires very rapid actions to stimulate extra investments in energy efficiency and the use of biogenic fuels.

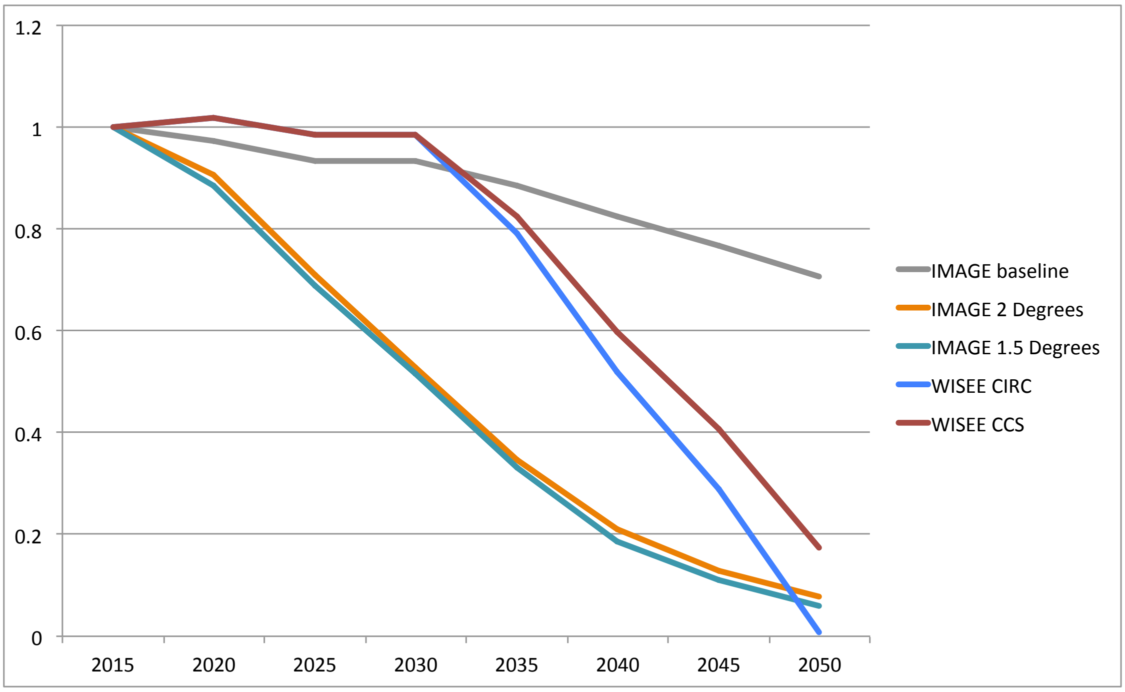


Figure 32. Projected CO_2 emissions in the iron & steel sector in the four decarbonisation scenarios and baseline, Europe (IMAGE and WISEE)

The large difference in timing of CO_2 emission reductions between IMAGE and WISEE has implications for the cumulative CO_2 emissions (Figure 33). Although the *CIRC* scenario reaches deeper emission cuts than IMAGE by 2050, the cumulative emission levels are significantly higher.

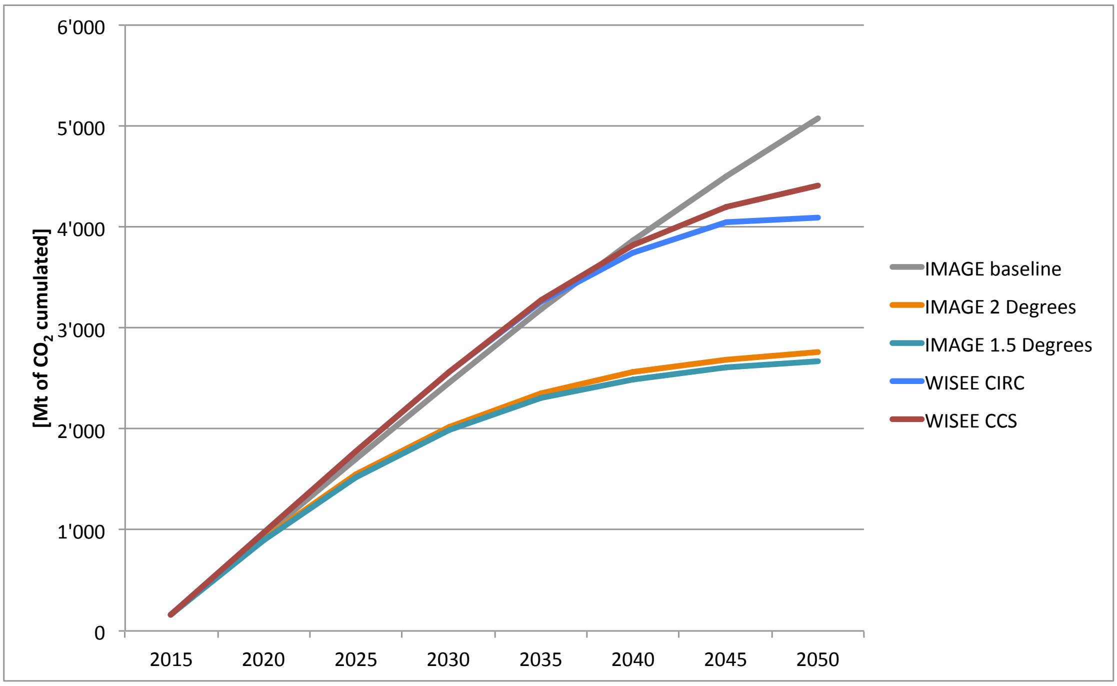


Figure 33. Cumulative CO_2 emissions in the iron & steel sector in the four decarbonisation scenarios and the IMAGE baseline, Europe

5.2.3 Plastics

5.2.3.1 Global vs European trends

The projected production of chemical products depends on the scenario, as it is assumed that more recycling takes place in more stringent mitigation scenarios (the same demand is assumed for all scenarios). For HVC, declining production volumes are shown in the *1.5 Degrees* scenario and relatively constant production volumes in the *2 Degrees* scenario for Europe (Figure 34).

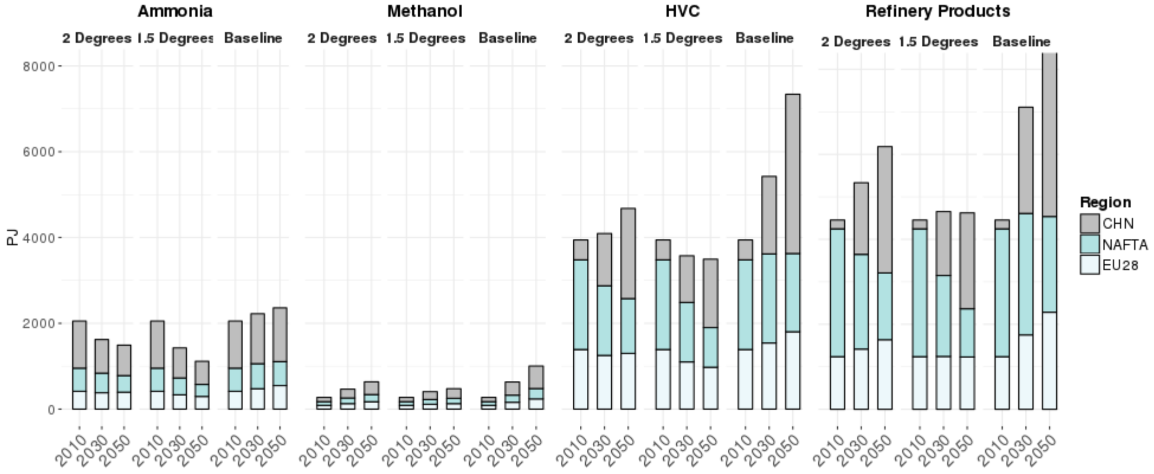


Figure 34. Projected production volumes for chemical products, Europe vs other world regions (IMAGE)

The 2050 Baseline values for refinery products falls outside of the scale of the figure, reaching up to 10 EJ

In our *2 Degrees* scenario, the chemical and petrochemical sector transitions from an oil-based sector to a biofuel and gas-based sector (Figure 35). In the *1.5 Degrees* scenario, gas plays a more important role as biomass is used in other sectors in combination with CCS to create negative emissions.

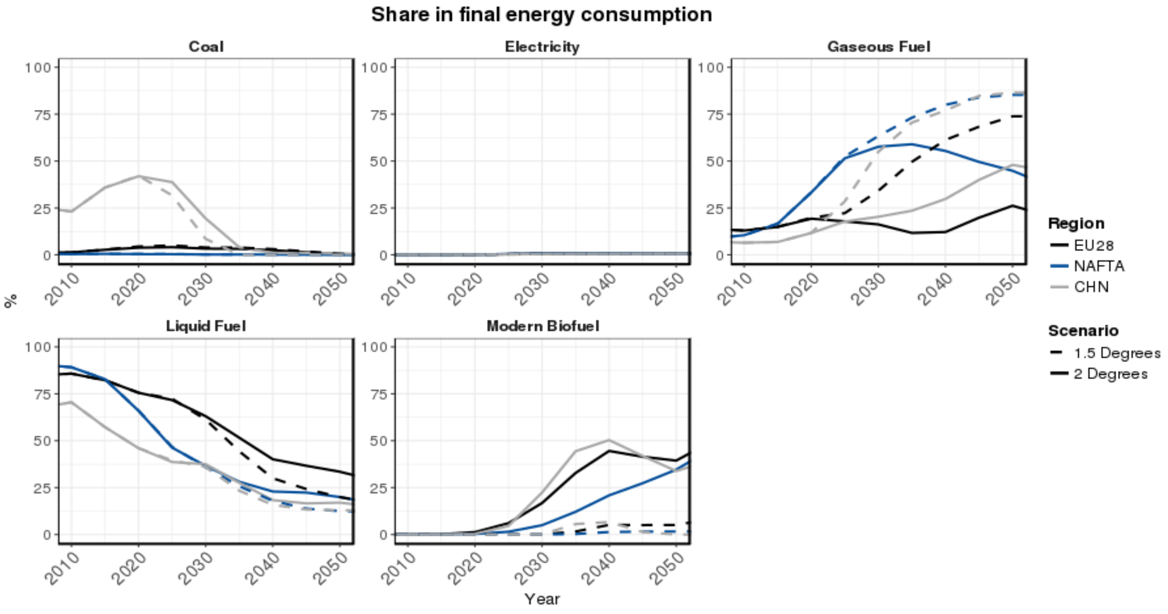


Figure 35. Projected shares of energy carriers in total final energy consumption of the chemical sector, Europe vs other world regions (IMAGE)

In both mitigation scenarios, European CO_2 emissions of the chemical and petrochemical sector decline by 60% in 2050 compared to 2010 levels (Figure 36). The CO_2 intensity for chemical products shows a marginal decreasing trend. Due to the greater dependency on gas, the CO_2 intensity as projected in the *1.5 Degrees* scenario is higher than observed for the *2 Degrees* scenario.

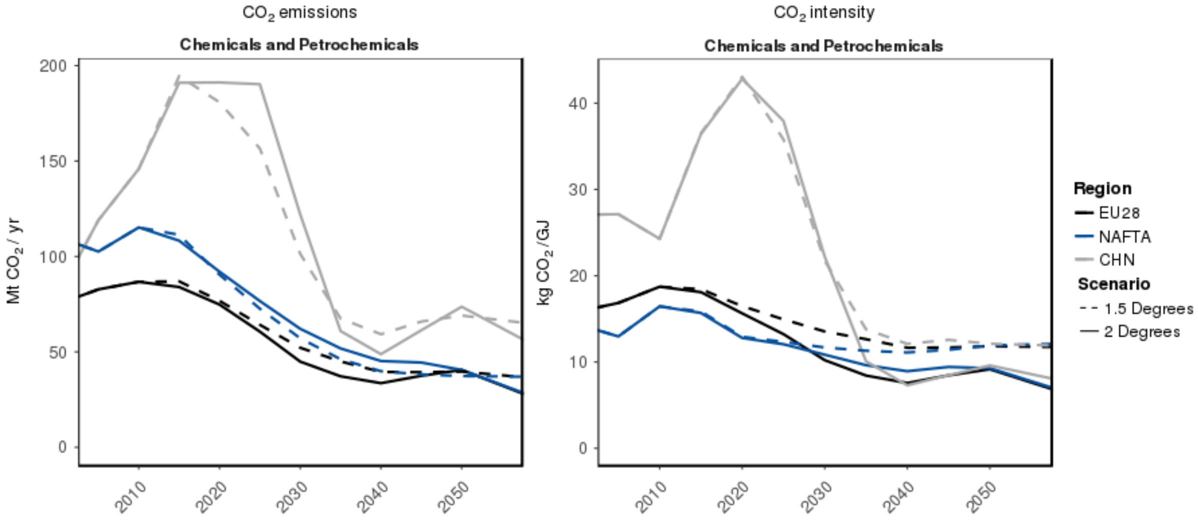


Figure 36. Projected CO_2 emissions and CO_2 emission intensity for (petro)chemical products (IMAGE)

5.2.3.2 European technology pathways

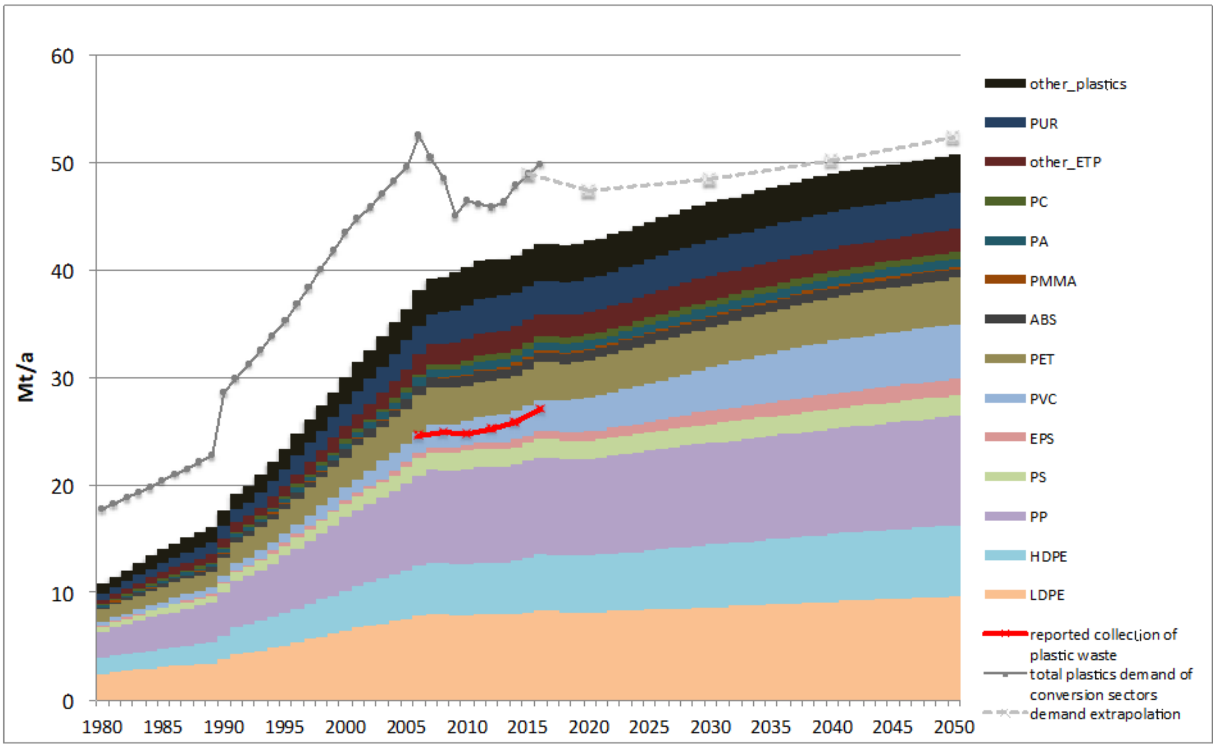
The plastics sector was analysed in detail by the WISEE model. The core of the WISEE model covers the value chain from crude oil refining until the “raw plastic”, which makes up the most energy intensive part. The WISEE model core was extended within the frame of the REINVENT project to explicitly model plastics demand and recycling flows (also see Chapter 3).

This section first presents the storylines connected to the two scenarios, then presents assumptions and derivations on recycling. Thereafter the scenario specific energy demand and resource flows are described, which were assessed in an bottom-up way and modelled as two scenarios for the total (aggregated) EU. A comparison of the WISEE scenarios with the more aggregated IMAGE/TIMER results can be found in Section 6.2.2.

Projection of waste flows

Plastic waste flows are a very relevant resource currently used only to a very low degree in Europe to produce new plastic products (see Figure 38), although it carries not only energy but also the molecules needed to produce new plastics. Figure 37 shows historic and projected waste streams modelled by assuming typical lifetimes of plastic products according to Geyer et al. (2017) and following the demand projections discussed in section 3.3.2. The grey line indicates this development of plastic demand of European plastic converting branches.

The most striking fact is the low collection rate of plastics (indicated by the red line) reported by statistics compared to the modelled waste amount connected to the demand of the EU converting industry. It shows that the plastic metabolism in Europe loses a significant amount of hydrocarbons, be it as net product exports (as plastic products) or be it as littering within Europe.



---

*) The flows indicated do not correspond to actual waste amounts within Europe but to the calculated waste amount resulting from the conversion of plastics within Europe. These converted products are often traded to abroad and then waste occurs there. On the other hand Europe also imports products that contain plastics, which has been produced and converted abroad.

Figure 37. Projected waste streams connected to plastic products supplied by European plastic converters

The slower increase of plastics demand results in a convergence of plastics demand and waste amounts in a year, because the total stock increase is low. As a consequence, there will be plenty of carbon feedstock from waste in the future, which could be made available for recycling.

The *CIRC scenario* builds on three recycling strategies for plastics:

- mechanical recycling,
- monomer recycling, and
- feedstock recycling.

Mechanical recycling is favoured in this scenario due to high energy and resource efficiency. However, the use of recyclates in technically limited, which is one reason why Europe exports recyclates to strongly growing markets, which may absorb these.

Monomer recycling implies resource and energy losses because the plastic is broken down to one of its monomers releasing heat and producing some fuel by-products. Pyrolysis is a typical process used for this purpose. Additional energy is needed afterwards to polymerise the monomer again. The newly built polymer has the same chemical and mechanical features than a virgin polymer. So unlike mechanical recycling, there are no restrictions on its use.

Feedstock recycling implies the highest losses because the plastic is broken down to its building molecules by a gasification of the plastic waste. The gasification product is a syngas containing hydrogen and carbon monoxide which may be used for the purpose of synthesizing platform chemicals. In the modelling the synthesis of methanol was regarded, which can be transformed in a further catalysis to platform hydrocarbons (olefins or aromatics) via a MtO (methanol-to-olefins) or MtA (methanol-to-aromatics) process. The MtO process has been installed in China at an industrial scale (using coal as a gasification educt) and can thus be regarded as proven technology whereas MtA, gasification and pyrolysis have been installed at a demonstration scale level and can thus still be regarded as to be developed.

During the processes of gasification and methanol synthesis a considerable amount of hydrogen is lost (30-40% and 50% respectively). If the carbon feedstock shall be kept in the metabolism (crucial requirement for carbon circularity), hydrogen has to be replenished by water electrolysis.

The CCS scenario only includes monomer recycling as a strategy. Figure 38 displays the different shares of the different strategies in the supply of plastics.

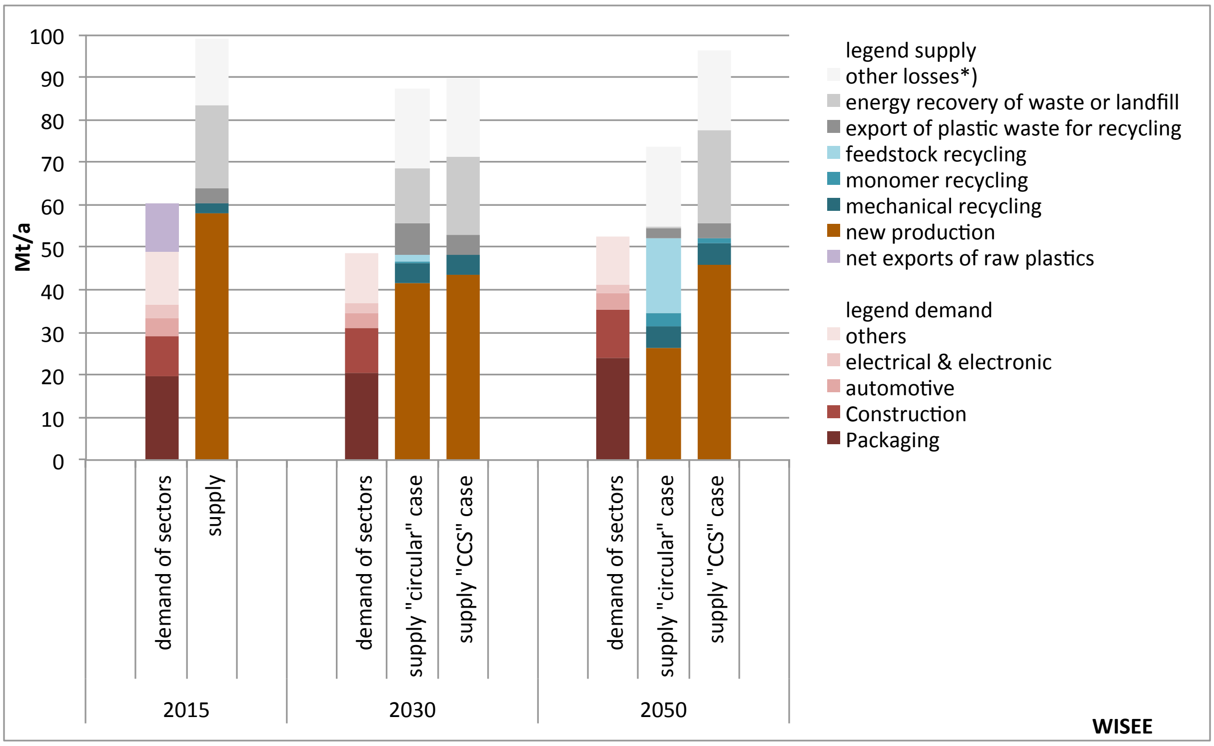


Figure 38. Projected balance in the plastics industry, Europe (WISEE)

The grey shaded parts of the supply columns in Figure 38 indicate streams leaving the “plastics metabolism”. If they could be avoided recycling could be enhanced and primary production be lowered.

The purple layered bar in 2015 represents the EU net exports of polymers. By 2030 these will diminish as EU assets will not be reinvested for export purposes.

Figure 39 and Figure 40 show primary energy use of the plastics value chain (from the resource to the polymer). The CCS scenario is characterized by a slight production decline until 2030. As in the *CIRC* scenario, this is mainly due to shrinking demand in primary polymers in Europe and a cut in EU net exports of polymers until 2030. The bulk of steam crackers in Europe has been built up before 1975 and so many of them reach their technical lifetime in the next decade. Disinvestment in steam crackers has already begun and is likely to continue in Europe. The recent overcapacities are projected to decrease until 2025 according to a typical lifetime of 50 years. Considerable amounts of waste- and bio-based production is projected to phase-in thereafter in the *CIRC* scenario, but some steam crackers will still be needed.

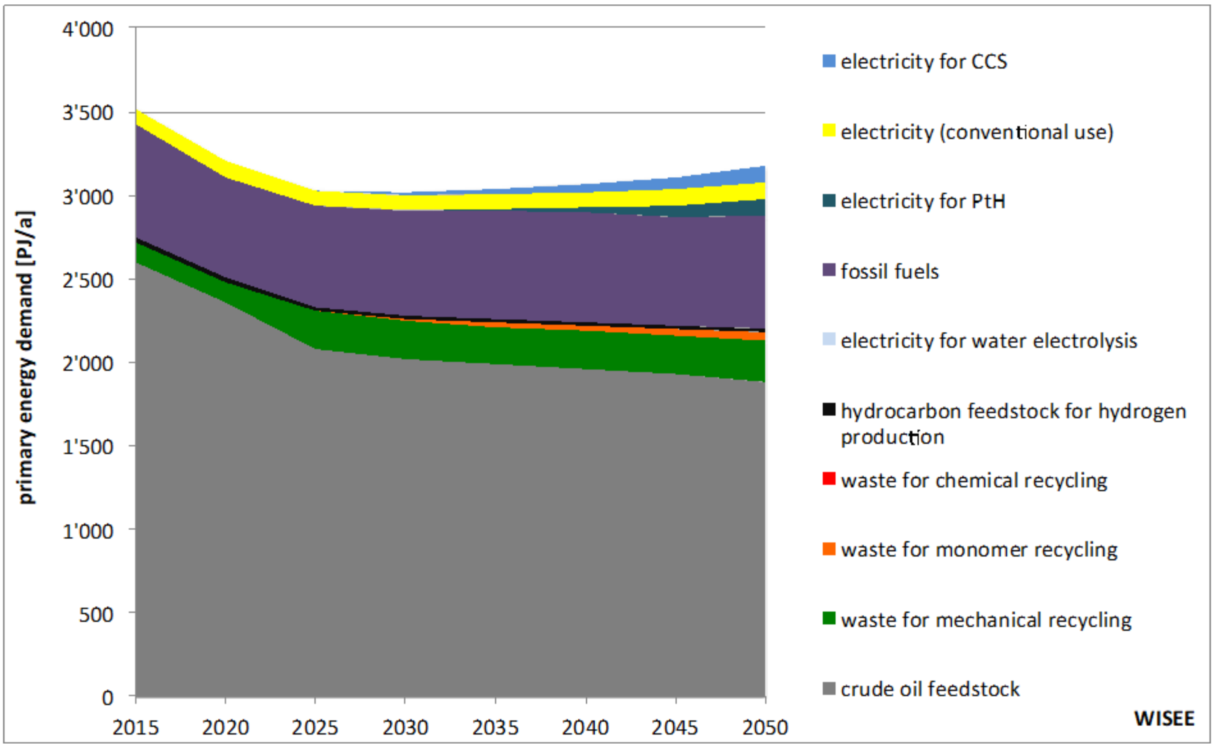


Figure 39. Projected primary energy use of the plastics industry in the CCS scenario, Europe (WISEE).

In the *CIRC* scenario, primary production capacities shift from steam cracking of oil products to an electricity-intensive methanol route based on plastic waste and black liquor from pulp production. High-temperature heat for the remaining steam cracking is supplied by biogas in the future.

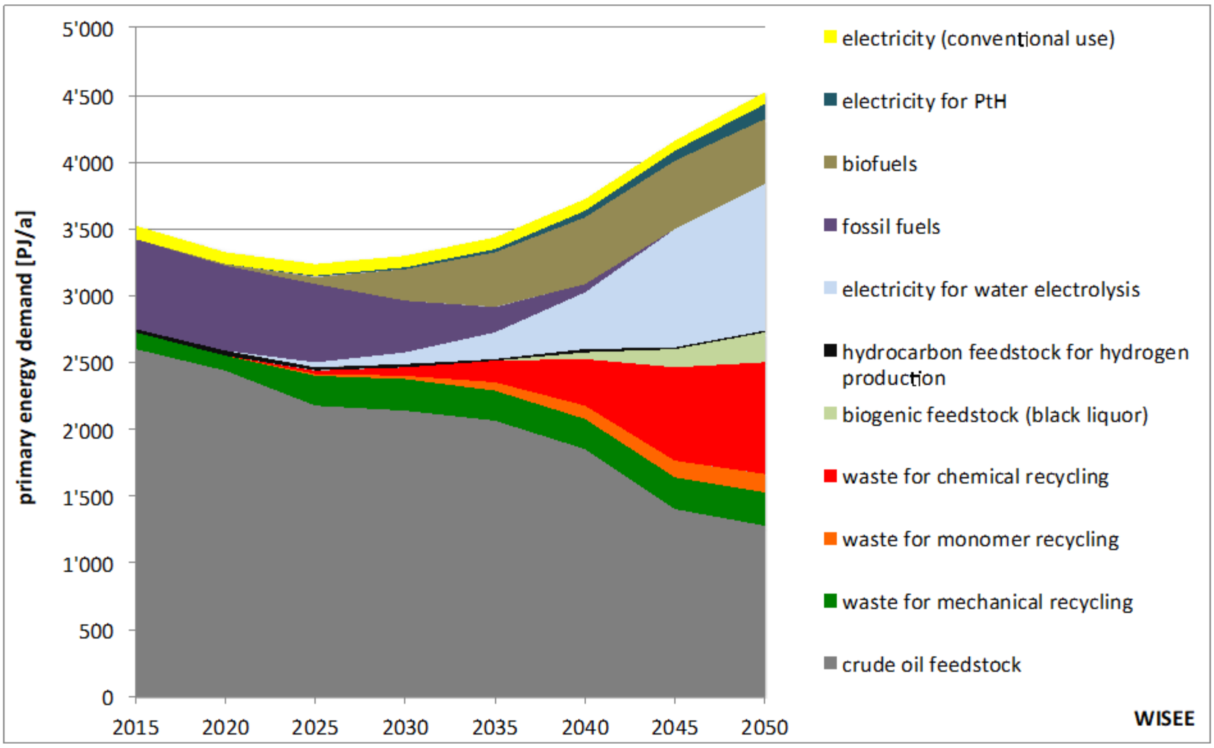


Figure 40. Projected primary energy use of the plastics industry in the *CIRC* scenario, Europe (WISEE)

The remaining grey-layered oil resources input could be replaced by bio-based Fischer-Tropsch fuels, which would result in additional net negative CO_2 emissions compared to the amounts already achieved by black liquor input (see Figure 41).

Unlike the development in iron & steel, WISEE shows an immediate cut in CO_2 emissions from the plastics industry. The cuts until 2030 are mainly due to shrinking demand, whereas later emission cuts are achieved by efficiency increase, thorough recycling strategies and a closing of carbon cycles.

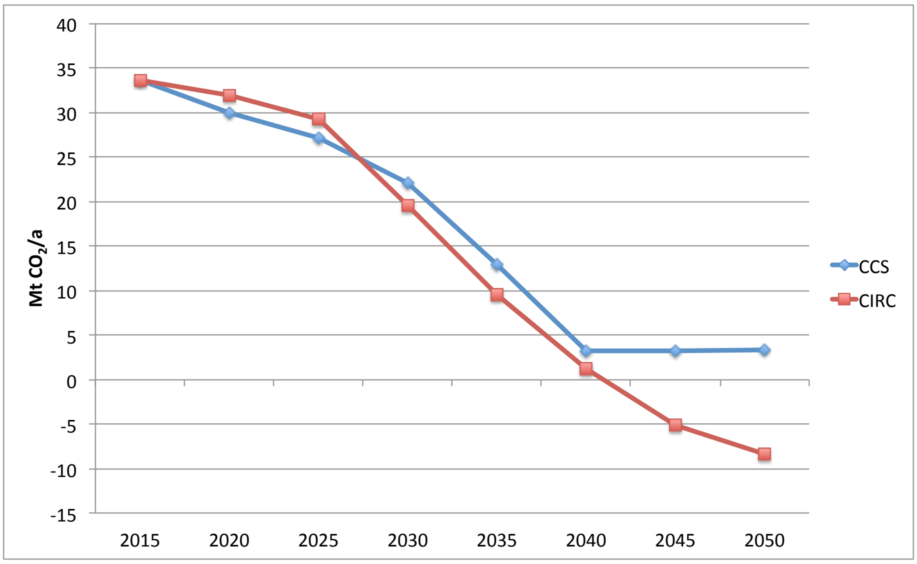


Figure 41. Projected CO_2 emissions of the plastics sector (WISEE)

Figure 42 shows the capacity development in steam cracking in the existing European petrochemical clusters during for the years 2020, 2030 and 2050. The map hints at possible locations, where Power-to-plastics could replace steam cracking and also shows at which locations considerable amounts of biogenic feedstock would be needed in 2050. The rather old, but very well vertically integrated petrochemical sites at Antwerp, in Western Germany, Northern Spain and in the Rhone delta have the deepest cuts in steam cracking capacities and could thus be adopters of power-to-plastic technologies. Further modelling of the adoption and diffusion of these technologies on a cluster level has been beyond the scope of this report.

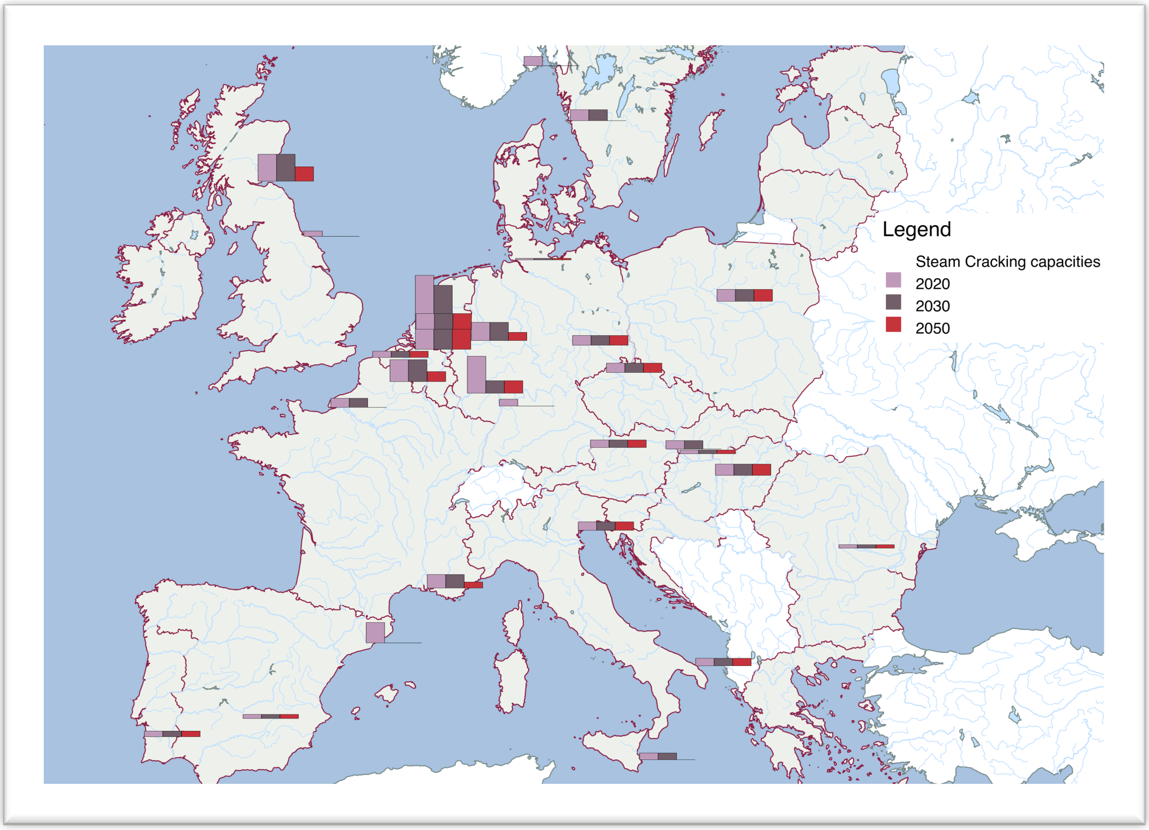


Figure 42. Map of projected steam cracker capacities in the *CIRC* scenario (WISEE)

WISEE and IMAGE scenarios are not further compared as there are differences in scope (complete polymer chain vs. HVC only), demand pathways (GVA of downstream industries driven vs. GDP per capita driven) and recycling strategies. An index-based comparison will however be presented in the comparison with literature (chapter 6).

5.2.4 Pulp and Paper industry

5.2.4.1 Global vs European trends

The IMAGE model projects that both chemical and mechanical pulp production in Europe increase by 0.75% p.a. (linear rate), which is less than the global average (Figure 43). The increasing use of recovered paper does not lead to an absolute decline in the need for virgin fibre over time. The

European markets for newsprint and other paper and paperboard products (including packaging) are relatively constant and declines after 2040. Only for the printing and writing product group the market is expanding in EU28, but to a lesser extent than the average global trend.

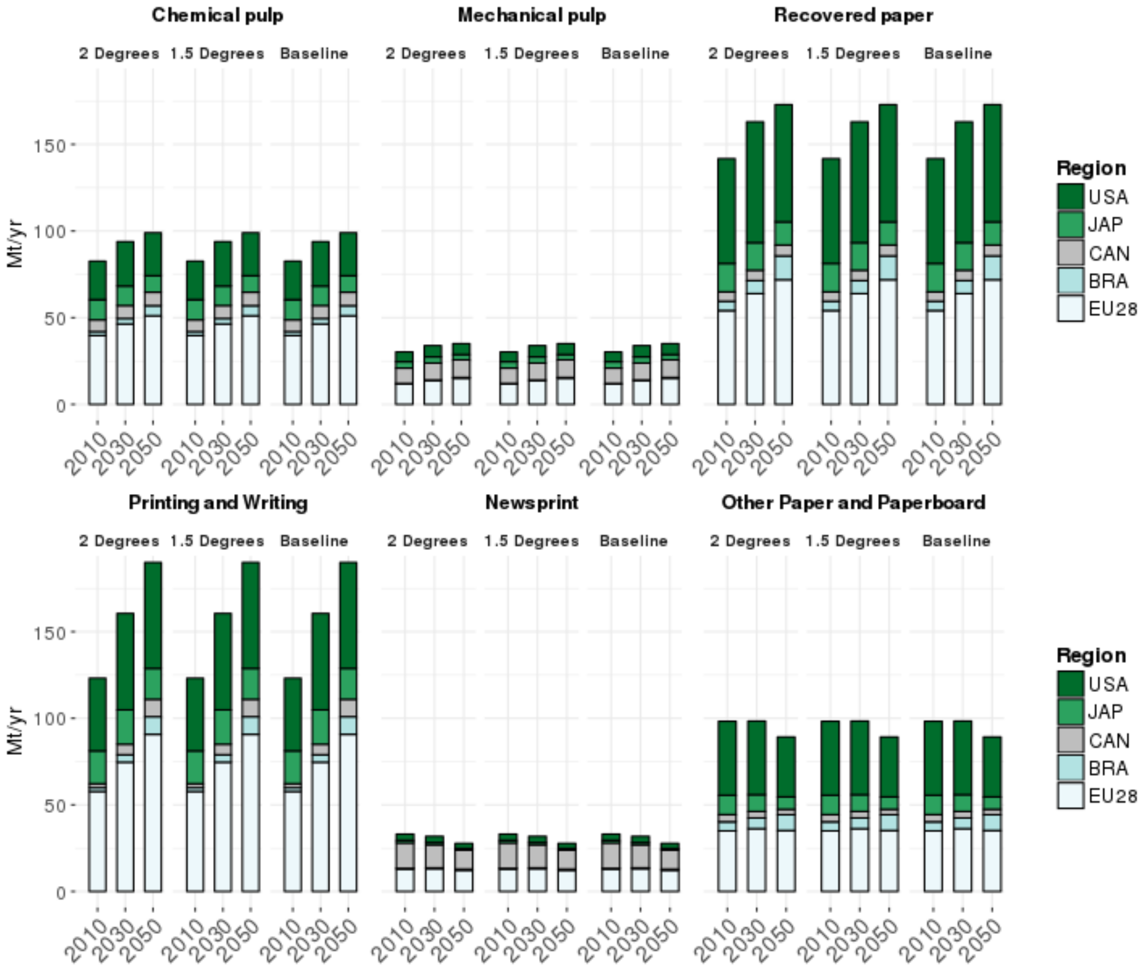


Figure 43. Projected production volumes for pulp and paper products, Europe vs other world regions (IMAGE)

The energy intensity of all pulp and paper products combined is projected to remain broadly constant, with a small efficiency improvement over time (Figure 44).

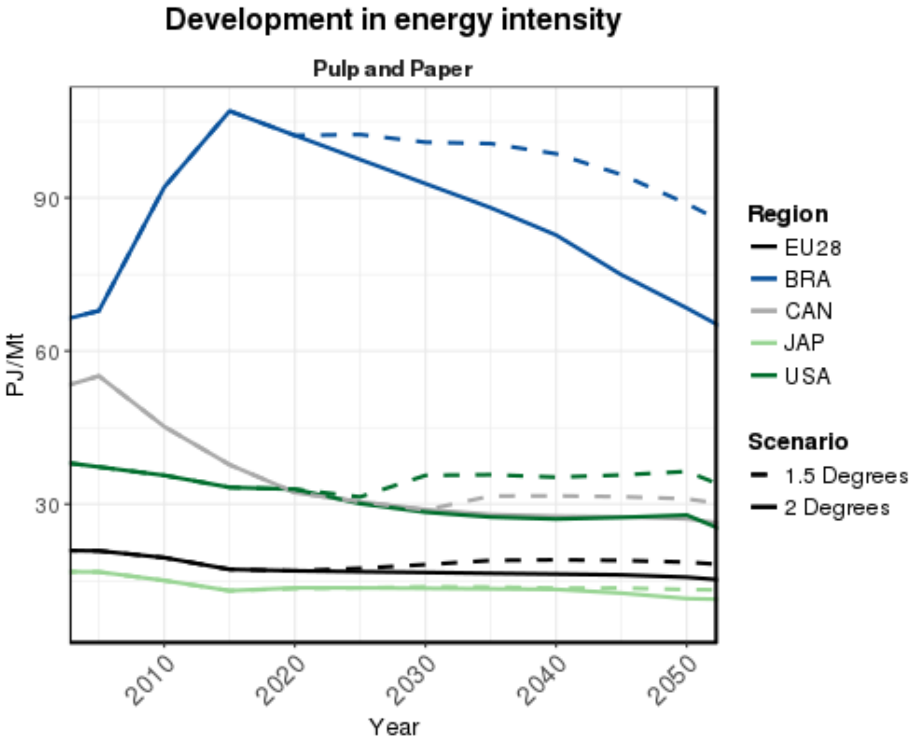


Figure 44. Projected energy intensity of pulp and paper products, Europe vs other world regions (IMAGE)

The pulp and paper industry is mostly powered on modern biofuels (e.g. black liquor), which will remain an important energy carrier for this sector under ambitious climate targets (Figure 45). Fossil fuels are projected to be phased-out of the industry by 2030, and to some extent replaced by bio-fuelled or electric boilers and heat pumps.

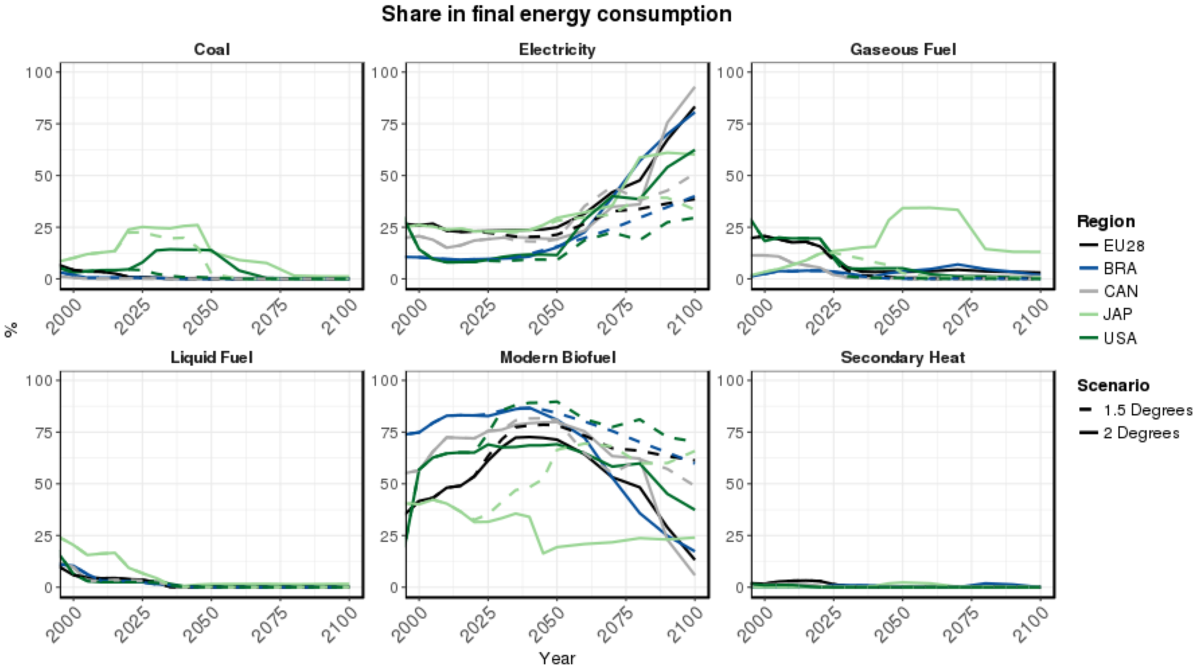


Figure 45. Share of energy carriers in total final energy consumption for pulp and paper products over time

The pulp and paper sector has a substantial potential for carbon capture and storage, which in our 1.5 °C scenario leads to large negative emissions in this sector (Figure 46).

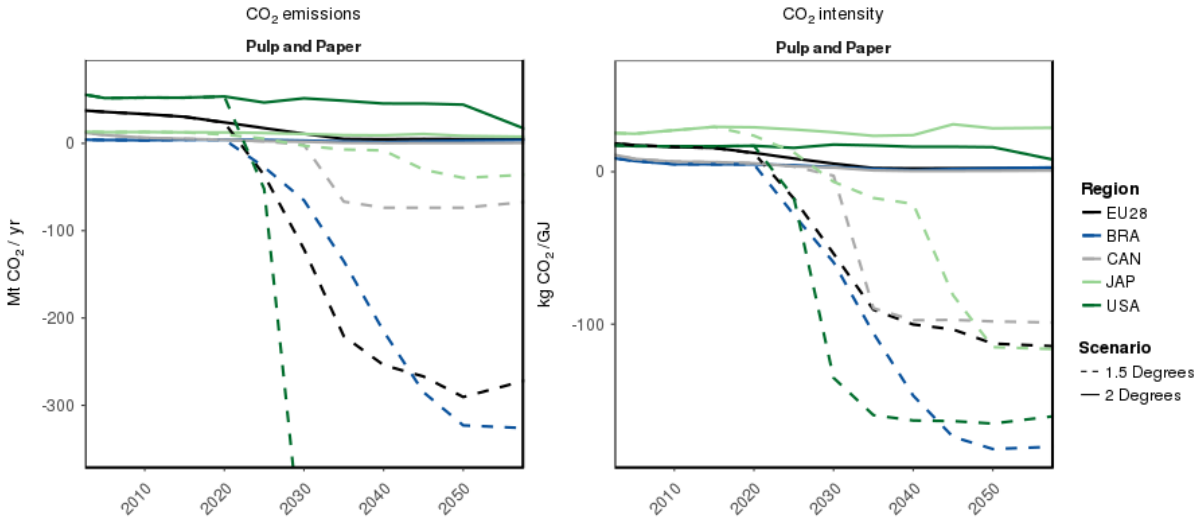


Figure 46. CO_2 emissions and carbon intensity for pulp and paper products over time

5.2.4.2 European technology pathways

The pulp and paper sector is characterised by its high thermal energy consumption. The largest share of (thermal) energy use is consumed during the evaporation and (pulp) drying processes (Carbon Trust, 2011; ICF Consulting Ltd, 2015). In the current day the process heat is delivered by steam boiler and other steam systems. In EU28 we find that the principle response strategy under ambitious climate targets in IMAGE is to replace and/or retrofit fossil fuelled boilers with biomass boilers. The *1.5 Degrees* scenario shows that the recovery boilers in the pulping industry are implementing carbon capture and storage systems, leading to negative emissions as presented above. In the papermaking sector some electrification is also projected to occur from 2040 onwards, assuming availability and commercialisation of heat pumps and electric steam boilers (Figure 47).

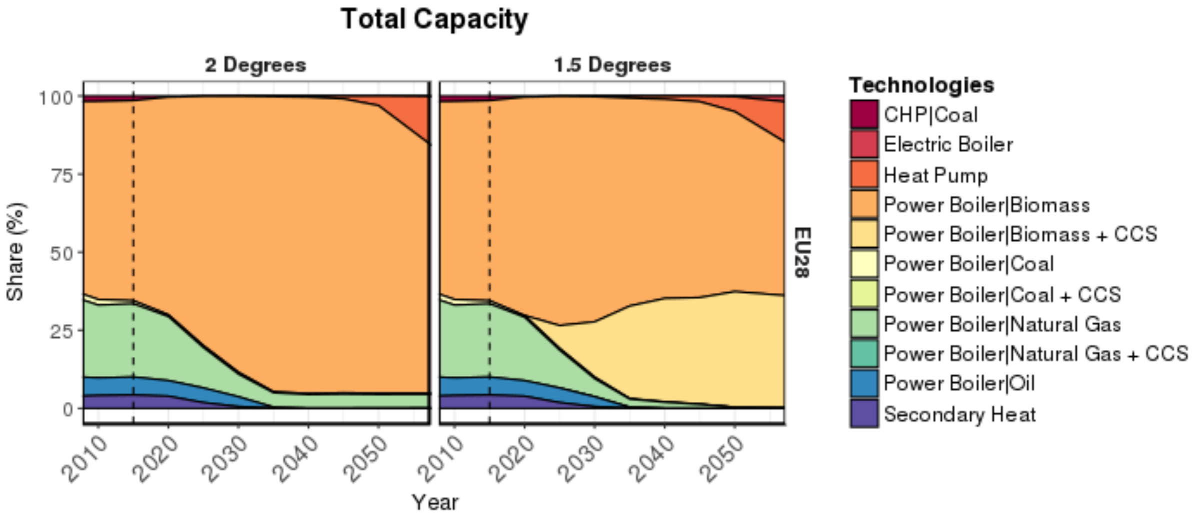


Figure 47. Projected technologies and energy use for heat supply in the pulp & paper industry, Europe (IMAGE)

The WISEE scenario CCS is very similar to the IMAGE *1.5 Degrees* scenario: biomass replaces natural gas, coal, and oil. This is a challenge in particular for sites without pulp manufacturing which rely strongly on recovered paper, i.e. sites outside Sweden and Finland, see also Figure 50. Today's pulping industry in the EU already relies to a strong degree on biomass, using wood chips and black liquor as a co-product from the pulping process. The CCS scenario assumes that CCS will be introduced from 2030 onwards in the pulping process by applying black liquor gasification and electricity and steam generation from the syngas in a combined cycle power plant. The application of this route allows for a boosting of electricity generation (see Figure 49) and a very efficient CO_2 capture. Like in the IMAGE *1.5 Degrees* scenario, biomass CCS results in net negative CO_2 emissions.

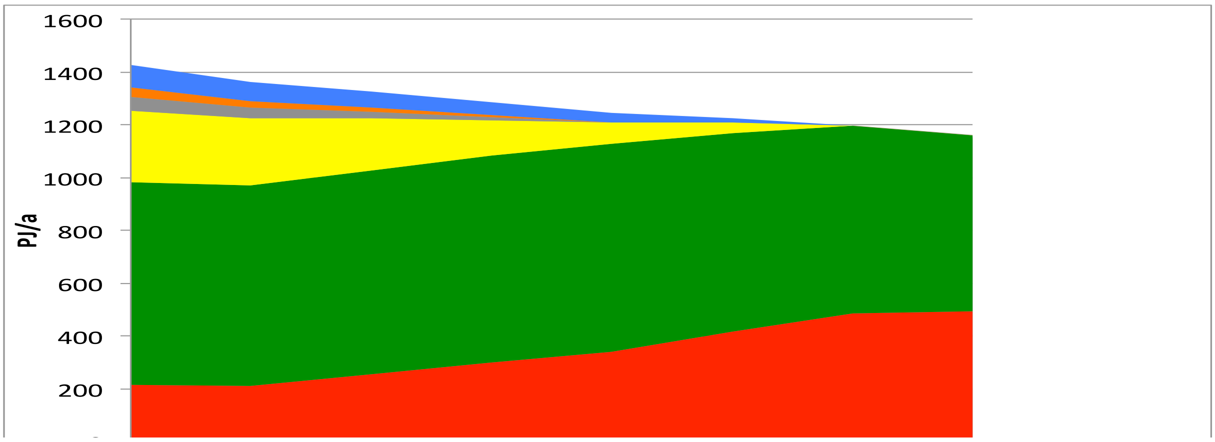


Figure 48. Projected primary energy use in the pulp & paper industry, Europe (WISEE)

In the WISEE *CIRC* scenario the pulp and paper sector has stronger relations with other sectors: For steam generation the sector uses electricity from renewables by applying electrode boilers and high-temperature heat pumps (see Figure 49). The hydrocarbon by-product black liquor is "exported" to the chemical sector, which uses the syngas from black liquor gasification to produce platform chemicals for plastics manufacturing (see above). As existing pulp and paper mills are often mostly self-reliant in regard to their electricity balance by applying CHP, the challenge in the *CIRC* scenario (where electricity generation from biomass is not maximised) is to connect the pulp and paper mills to strong electricity grids to allow interchange. Black liquor cannot be exported as it contains useful chemicals, which can be reused in the pulping process. Syngas on the other hand is also not easy to transport because of its low energy content in regard to volume. So export to the chemical industry would be preferably in the form of a platform product like methanol produced onsite (requiring additional hydrogen/electricity) and shipped from ports in the Northern countries to existing coastal sites of the petrochemical industry in Northwestern and Southern Europe.

The infrastructural challenge of the CCS scenario is to transport the CO_2 from the pulping plants to CO_2 storage sites. Figure 50 displays the geographical distribution of today's CO_2 emissions of the sector and also includes biogenic CO_2. The blue circles display the locations of plants with an economic focus on pulp making, whereas the green ones represent sites which create their most value added with paper making. In both categories, however, there are plants with integrated production of pulp and paper.

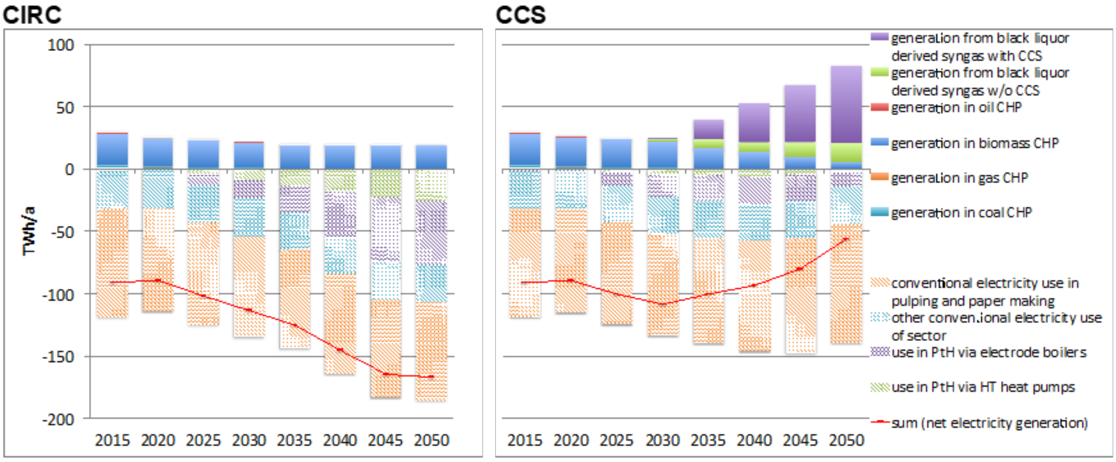


Figure 49. Projected electricity balance in the paper & pulp industry (WISEE)

The map shows that the main area of interest is the Baltic coast, but there are also sites in the inland of Sweden and Finland, as well as in Portugal. Due to the near-shore location of most large sources CO_2 could be transported via ships to suitable (offshore) storages.

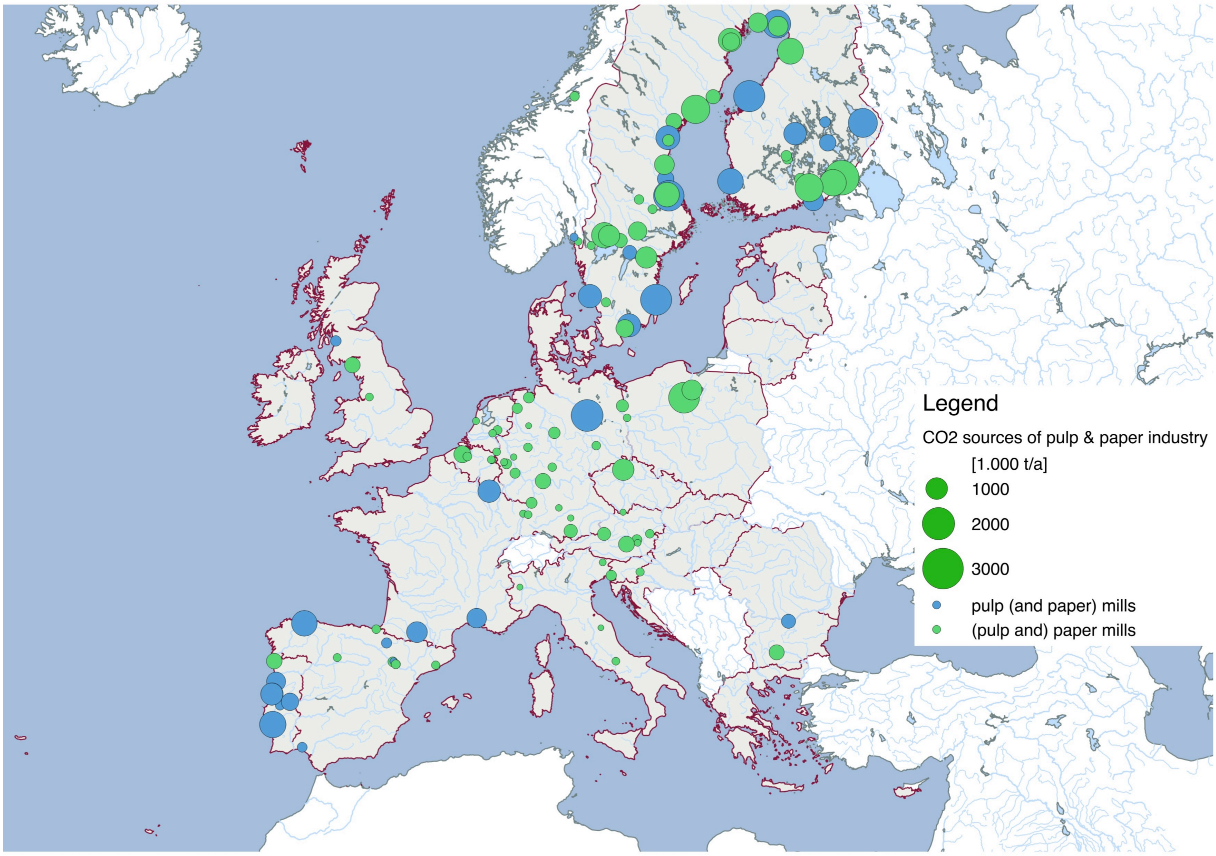


Figure 50: Map of CO_2 sources in the pulp & paper industry (based on eprtr data of EEA)

In the CCS scenario it was assumed that not all pulping plants will use CCS as this may not be economic for Nordic inland sites.

Figure 51 compares CO_2 emissions of the four IMAGE and WISEE scenarios. In the medium term, the IMAGE *2 Degrees* scenario and the two WISEE scenarios show similar emission trajectories. In the 1.5 Degree scenario of IMAGE, however, a very rapid adoption of CCS takes place leading to much stronger reductions from 2020 onwards than in the WISEE CCS scenario in which this technology is adopted more slowly (from 2030 onwards). The WISEE *CIRC* scenario reaches net zero emissions by 2045. In this scenario net-negative emissions are achieved by storage of biogenic carbon in plastics which is not depicted in Figure 51 as they are allocated to the chemical industry.

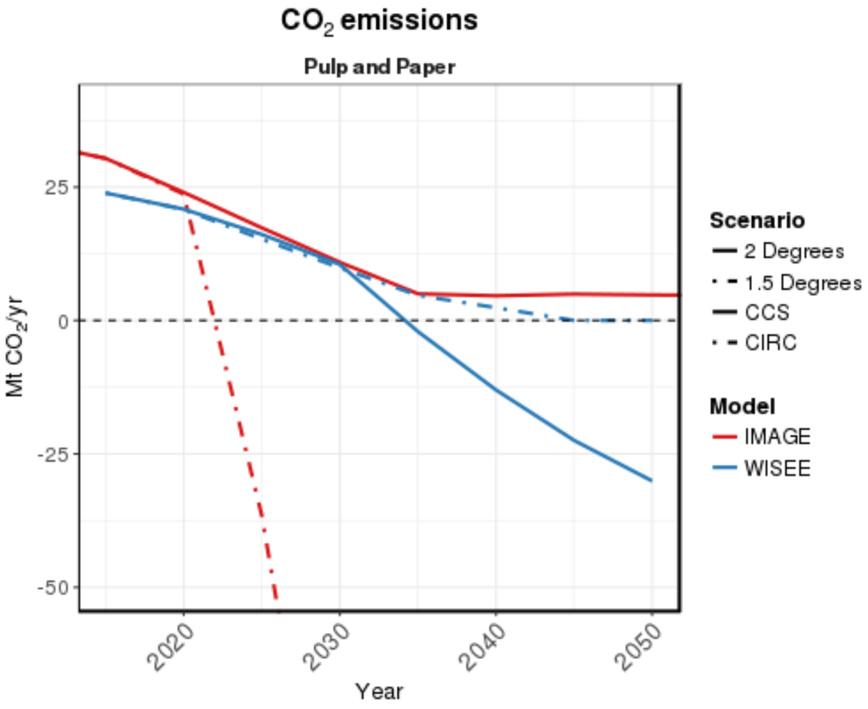


Figure 51. Projected CO_2 emissions of the pulp & paper industry (IMAGE and WISEE)

5.2.5 Meat and dairy

5.2.5.1 Global vs European trends

In IMAGE the global production volumes of meat and dairy are projected to increase by respectively 2% and 1% annually (Figure 52). The trend in Europe is increasing more slowly at an average 0.5% annual increase. In the mitigation scenarios, no different consumption patterns are assumed here – although it has been shown that dietary changes could reduce greenhouse gas emissions from agriculture substantially (Stehfest et al., 2009; van Sluisveld et al., 2016; van Vuuren et al., 2018). Here, we focus mainly on the food processing industry.

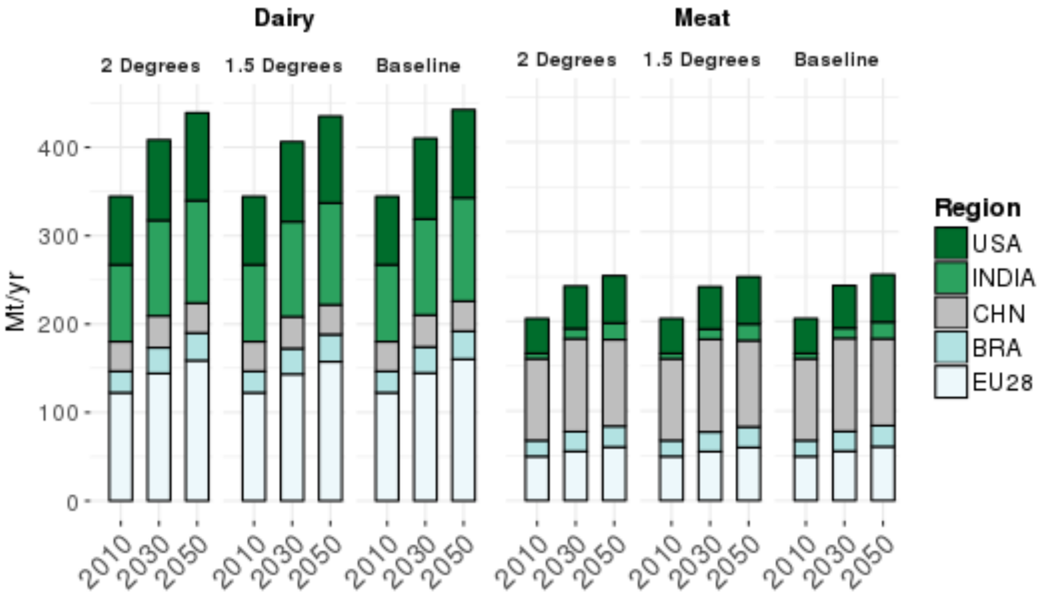


Figure 52. Projected production volumes for food products (IMAGE)

*Dairy represents the total of Milk and Butter & Cream, while meat represents the total of beef, pork, poultry, sheep, goat and other meat and animal fats.

The IMAGE model projects a slowly declining energy use per unit of production for the food processing sector in Europe (see Figure 53). The current energy intensity of Europe is already relatively low compared to regions such as the USA and especially Brazil.

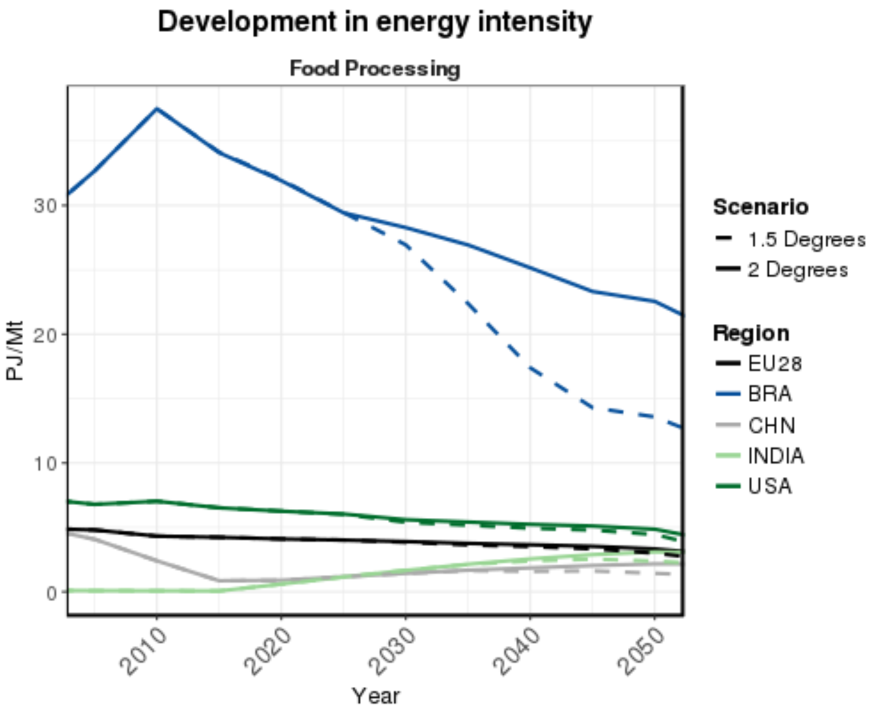


Figure 53. Projected energy intensity for animal food products, Europe vs other world regions (IMAGE)

The decarbonisation strategies, and especially our *1.5 Degrees* scenario, show a transition from natural gas towards modern biofuels in food processing in Europe (Figure 54). Currently, more than 60% of energy is provided by natural gas in the food processing industry in Europe, the remainder being provided by liquid fuels and biofuels. By 2050, about 60% is provided by biofuels in the *2 Degrees* scenario and almost 100% in the *1.5 Degrees* scenario.

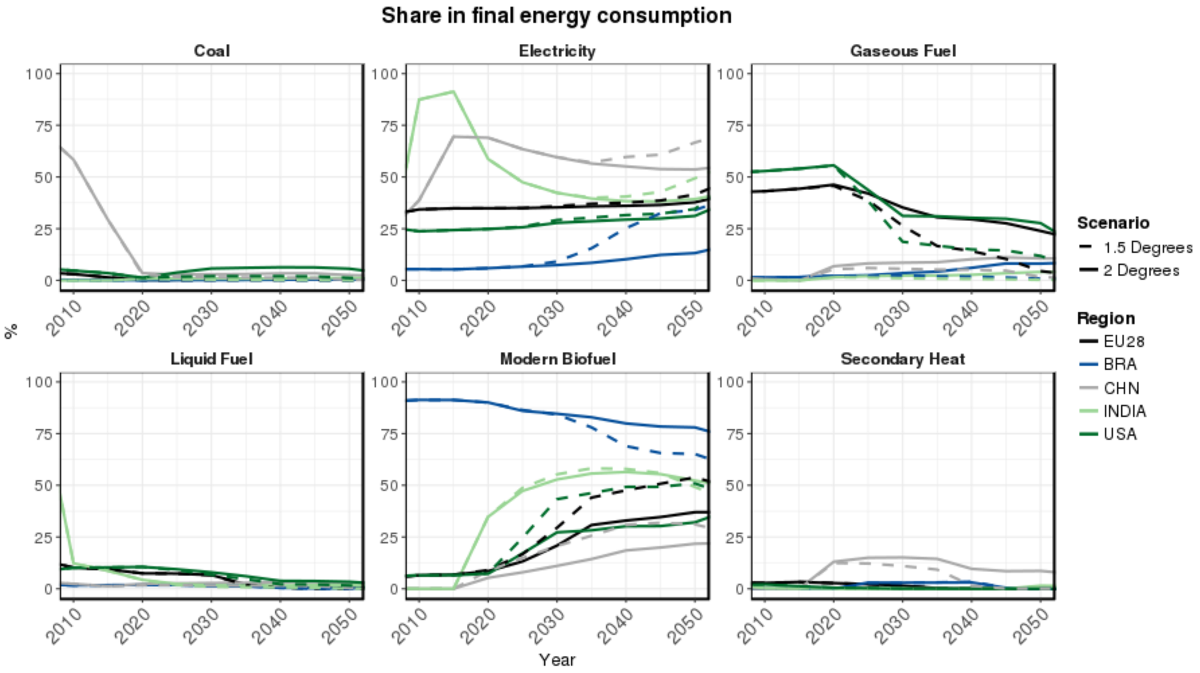


Figure 54. Projected share of energy carriers in total final energy consumption for food processing (IMAGE)

This switch from natural gas to biofuels leads to an almost complete decarbonisation of the food processing industry in the *1.5 Degrees* scenario (Figure 55). In the *2 Degrees* scenario, CO_2 emissions are approximately halved.

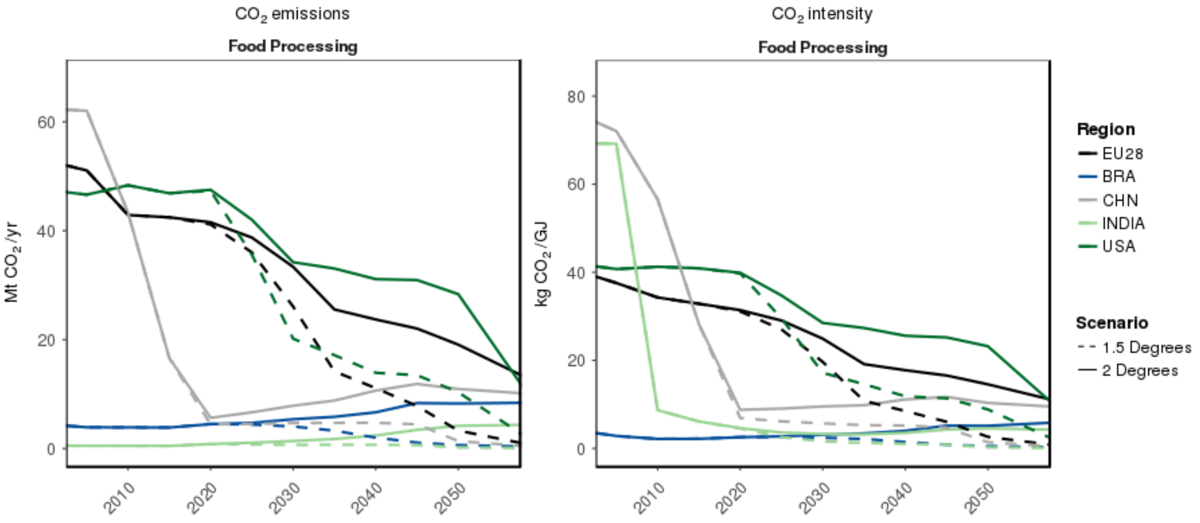


Figure 55. Projected CO_2 emissions and CO_2 intensity of the food processing industry, Europe vs other world regions (IMAGE)

5.2.5.2 European technology pathways

The food processing sector is a heterogeneous sector, with a wide range of food products that each have different energy requirements. The IMAGE model differentiates for low and high temperature grades in the food processing sector (Figure 56). For high temperature processes, the decarbonisation scenarios show a gradual shift from mostly natural gas based steam boilers to bio-fuelled steam boilers. The *1.5 Degrees* scenario also shows some electrification via electric boilers by 2050. A similar transition is observed for low temperature processes, although the lower temperature requirements allow the adoption of heat pumps by 2025.

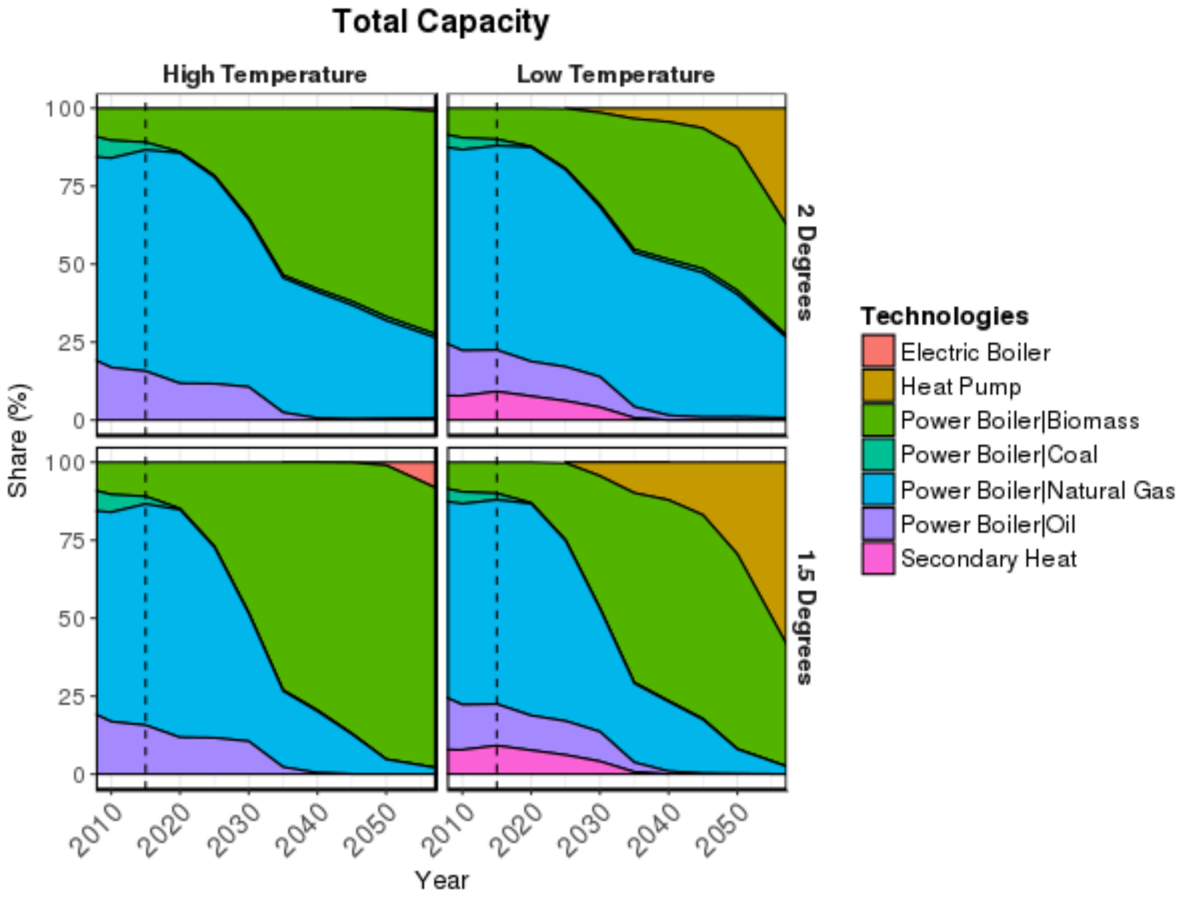


Figure 56. Projected technologies in the food processing industry, Europe (IMAGE)

6 Comparison with literature

In this section the scenarios of the IMAGE and WISEE models are compared to existing industry decarbonisation scenarios in literature. For the existing studies, we use the same ones as analysed by the earlier REINVENT report D4.1 (Schneider et al., 2017).

6.1 Industry decarbonisation scenarios

Various studies have presented possible futures of industrial decarbonisation for the industry as a whole. Figure 57 shows that CO_2 emissions of the total industry as projected by the IMAGE *2 Degrees* scenario is within the literature range, although IMAGE describes an overall more ambitious decarbonisation trajectory towards 2035. However, from 2040 onwards, a larger number of studies show a greater contribution from industry to mitigation than the IMAGE *2 Degrees* scenario.

The *1.5 Degrees* scenario, however, shows much faster and deeper emission reductions than existing studies. Especially after 2025, major additional mitigation efforts are adopted leading to an almost complete decarbonisation by 2040.

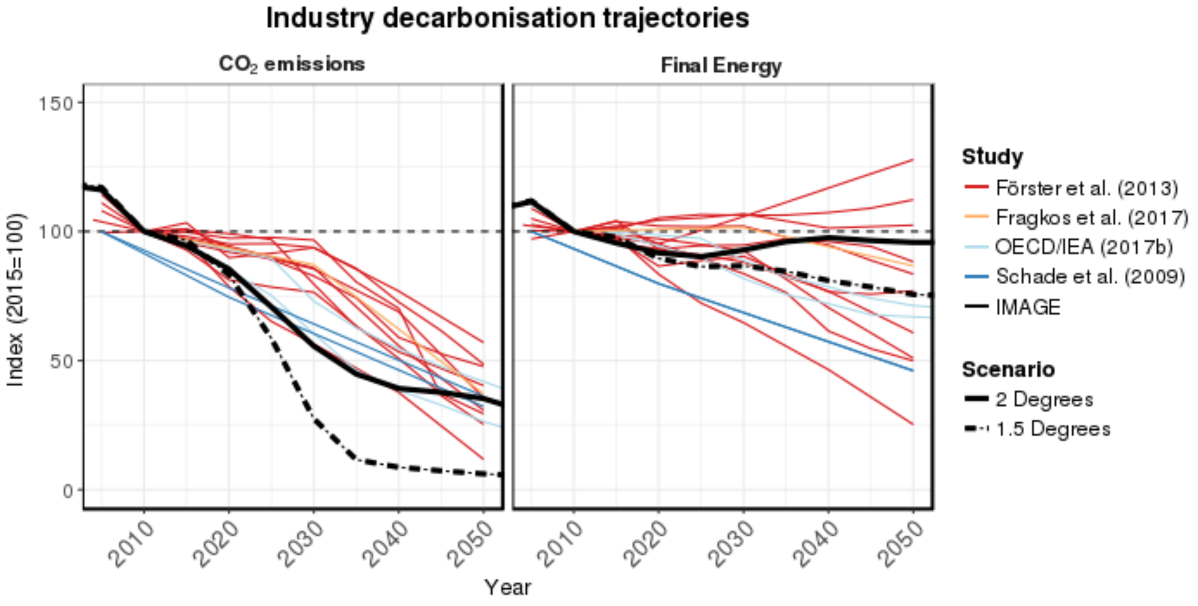


Figure 57. Projected CO_2 emissions and final energy use for the industry sector as a whole across various studies, Europe

6.2 Sector specific decarbonisation pathways

6.2.1 Steel

Future pathways on (primary) steel production depict an overall growth over time (Figure 58). The IMAGE model projections remain in the literature range but at the lower bound of the range.

Most mitigation pathways for the iron and steel sector show a reduction of about 10%-35% in total energy consumption by 2050 (Figure 59). The IMAGE scenarios and the WISEE *CIRC* scenario are within this range, while energy demand in the WISEE CCS scenario is more or less constant. A notable difference is that in the IMAGE scenarios, energy consumption reduces earlier than shown by existing studies.

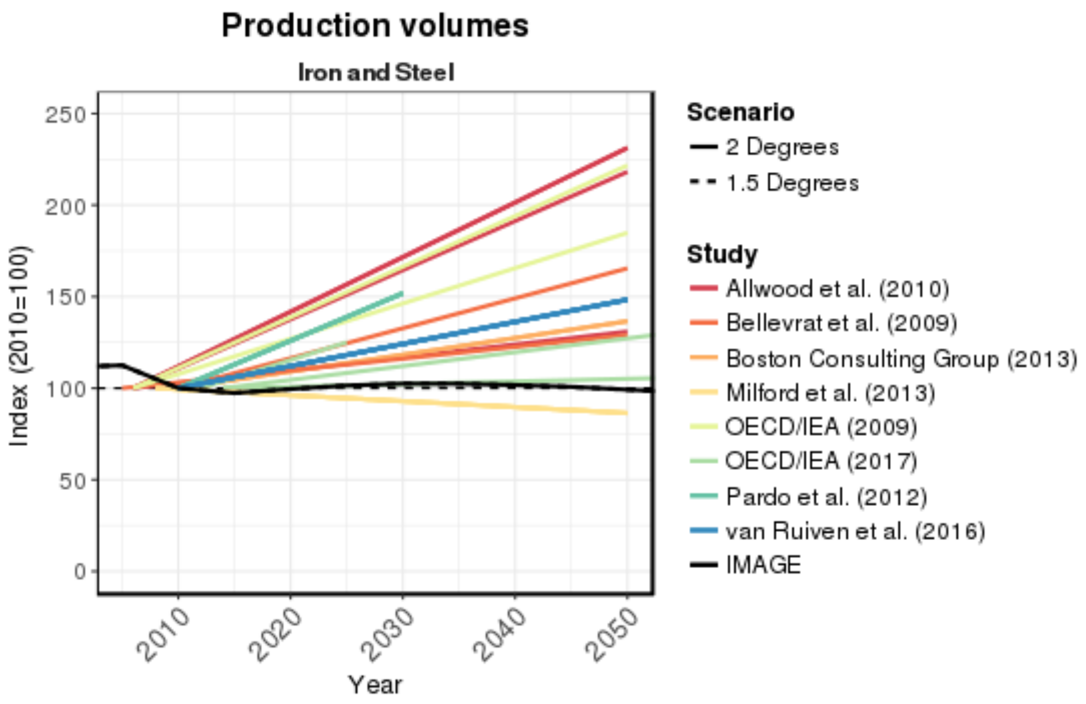


Figure 58. Projected production volumes of primary steel in the iron and steel sector across various studies

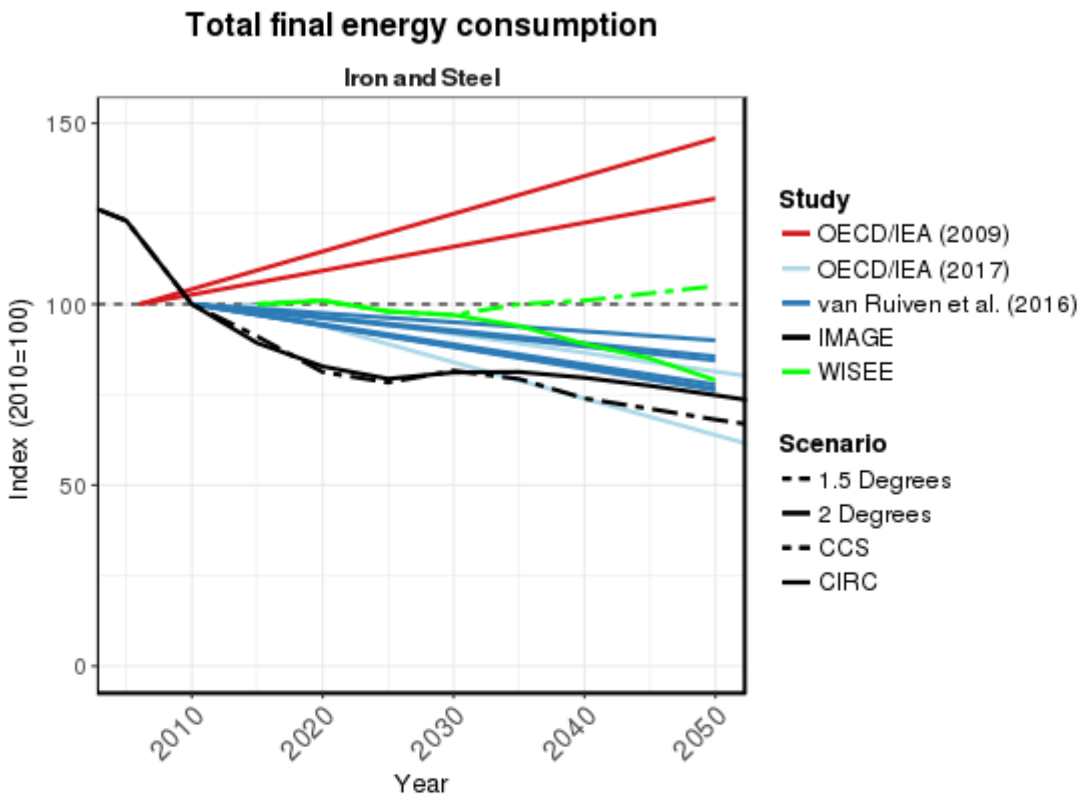


Figure 59. Projected final energy consumption of the iron and steel sector across various studies

CO_2 emissions from the iron and steel industry in the IMAGE scenarios are at the low end of range found in literature (Figure 60). In the WISEE scenarios, on the other hand, CO_2 emissions are reduced much later than in existing scenarios, and from 2030 shows very rapid reductions.

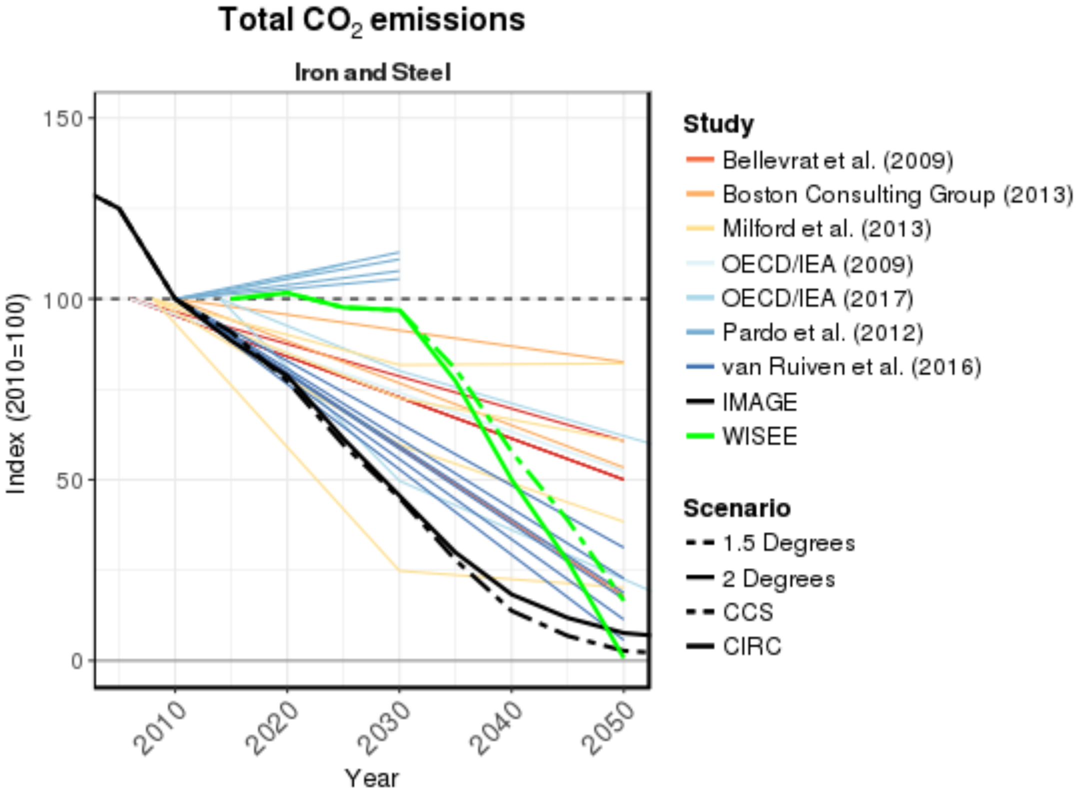


Figure 60. Projected CO_2 emissions from the iron and steel sector various studies

6.2.2 Plastics

Existing mitigation scenarios of the plastics sector show production volumes that do not deviate much from business-as-usual (Figure 61), depicting long-term sustained annual growth of about 2-4% of 2010 production levels. Both the IMAGE and WISEE scenarios show much lower productions volumes (practically constant and even declining in the IMAGE *1.5 Degrees* scenario due to higher assumed recycling rates).

In the IMAGE scenarios, future energy use of the chemical sector is within the range as reported in literature (Figure 62). In the *2 Degrees* scenario the projections are close to the upper bound, while the *1.5 Degrees* scenario is closer to the lower bound. The WISEE scenarios show little variation in energy demand. Given that this is also the case for production levels, it means that energy efficiency does not improve much over time in the WISEE scenarios.

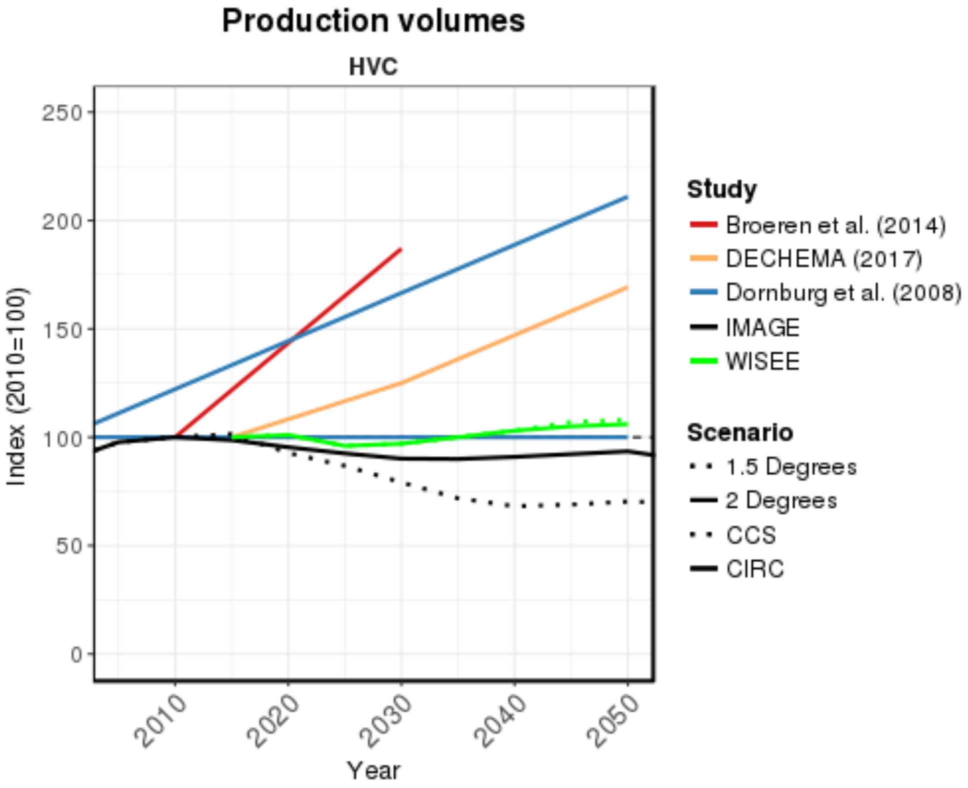


Figure 61. Projected production volumes of high value chemicals across various studies

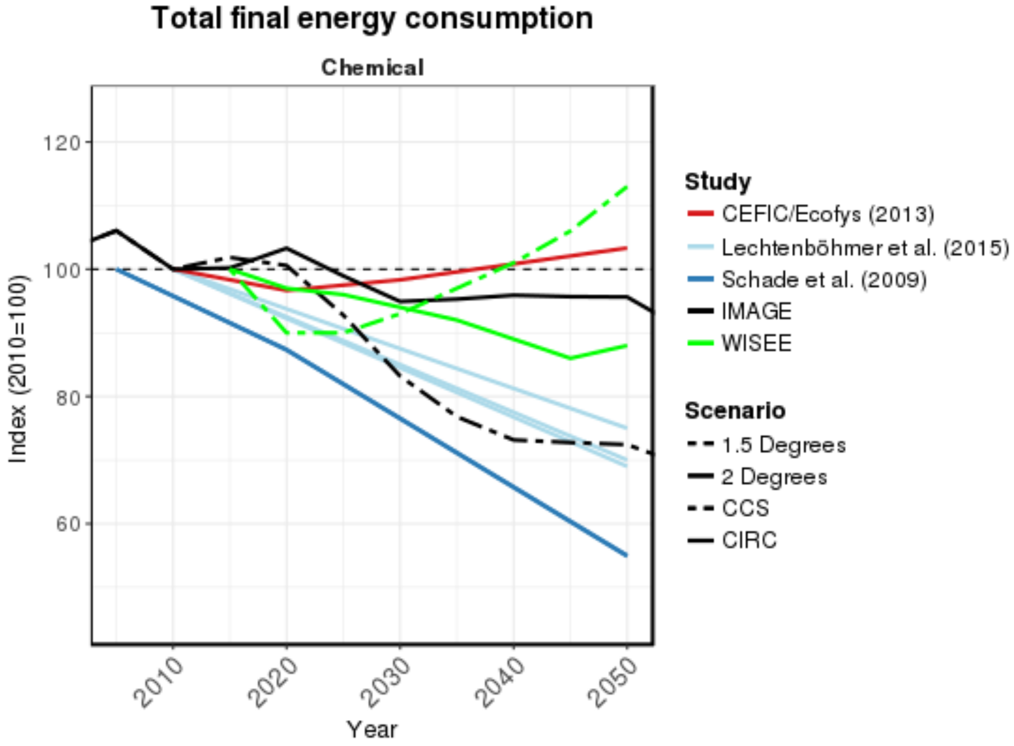


Figure 62. Projected final energy consumption of the chemical sector across various studies

The IMAGE scenarios show similar CO_2 reduction pathways as other scenario studies for the chemical industry. However, the mitigation potential appears to level off after 2040 in the IMAGE scenarios, stabilising at about 55% emission reductions by 2050 compared to 2010 levels, irrespective of the climate scenario.

The WISEE model, representing the plastics supply chain in more detail, shows a more rapid decline in the plastics sector after a short period of system inertia. In contrast to the broader literature and the IMAGE model, the WISEE CCS scenario shows negative emissions by 2040. In the *CIRC* scenario, total emissions are plateauing by 2040 at about 10% of the 2015 level.

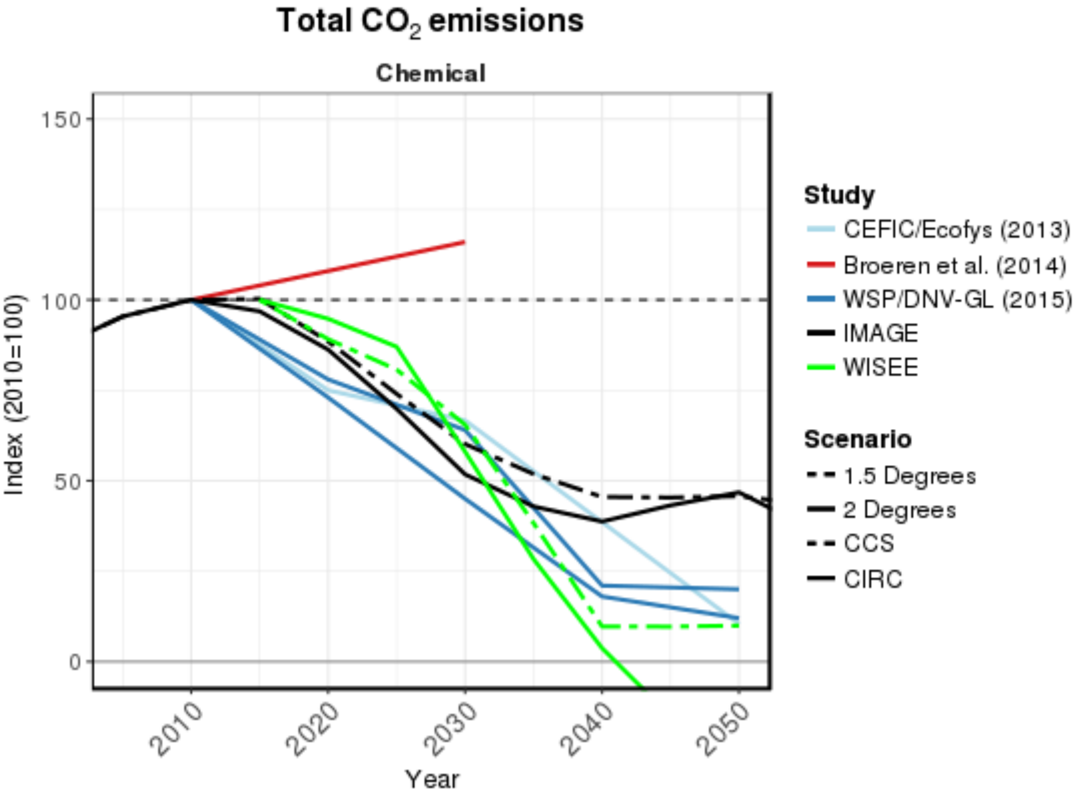


Figure 63. projected direct CO_2 emissions of the chemical sector across various studies

6.2.3 Pulp and paper sector

A wide range of possible futures is considered for the total final energy demand for the pulp and paper sector. The broader literature outlines futures that double the total energy consumption by 2050 to futures that nearly half the energy demand in the sector. The IMAGE model shows an increase in total final energy consumption for the pulp and paper industry, as the pulp and paper sector is not restricted to energy sources with a carbon content. Instead, due to the overall high availability of bioenergy sources and a need to offset remaining emissions in the atmosphere with negative emissions, the total final energy consumption is expanding under the *1.5 Degrees* scenario.

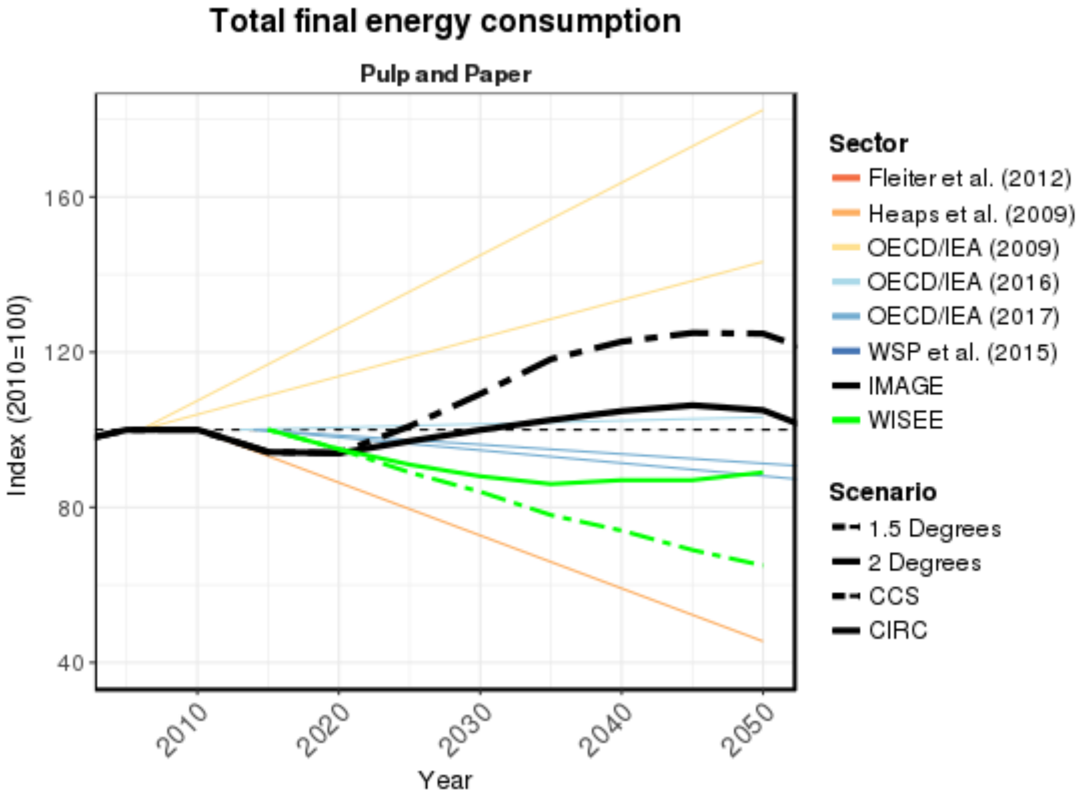


Figure 64. Projected final energy consumption of the pulp and paper sector across various studies

Our IMAGE and WISEE scenarios provide more ambitious pathways for the pulp and paper industry than presented in the broader literature (Figure 65). In both the WISEE CCS and IMAGE 1.5 Degree scenario, the Pulp and Paper sector is transformed into a carbon sink before 2035, which is much more ambitious than existing literature on decarbonisation pathways for the pulp and paper sector. For the IMAGE model, this only happens for high carbon prices, as implemented in the *1.5 Degrees*, as sufficient exogenous pressure for the pulp and paper sector to include carbon capture and storage installations into chemical pulping plants are needed. In the *2 Degrees* scenario, the carbon tax is assumed not to lead to the adoption of these technologies, leading to an emission reduction of 90% of 2010 levels by 2035. In the WISEE *CIRC* scenario, zero emissions are achieved.

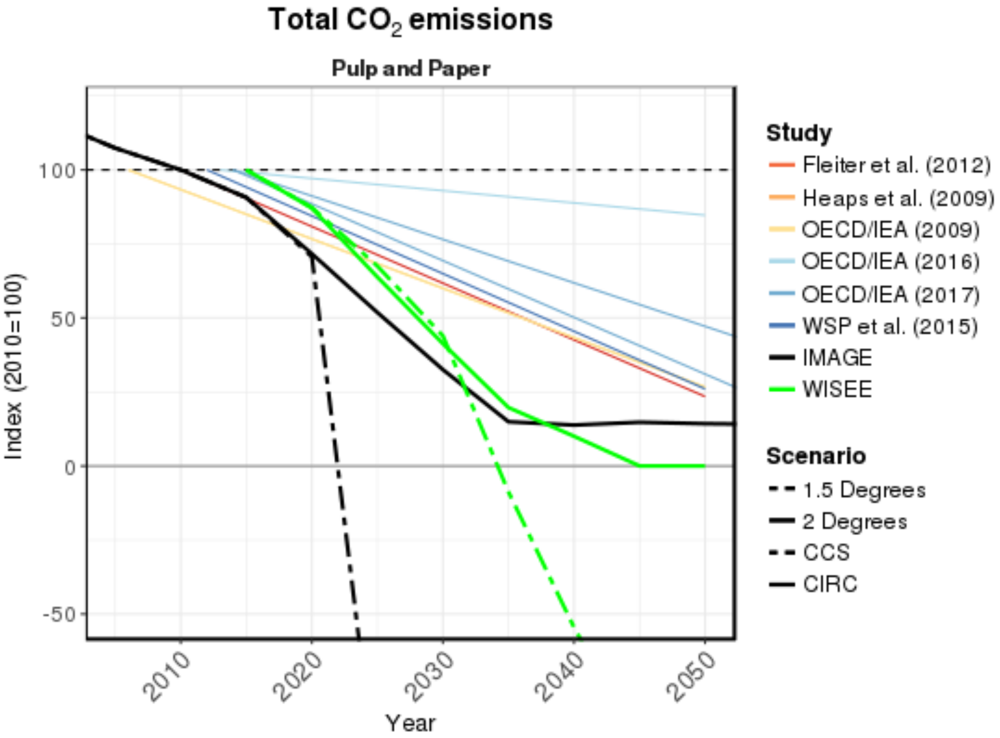


Figure 65. Projected CO_2 emissions of the pulp and paper sector across various studies

6.2.4 Meat and dairy sector

There is only one decarbonisation study with European projections for production in the dairy and meat sectors which we can compare our results to (Figure 66). The IMAGE projections of production volumes of the dairy sector are similar to the long term projections by OECD/FAO (2017), showing an annual (linear) increase of 0.5%. For the meat sector, the projections between OECD/FAO (2017) and IMAGE deviate in the short term, but show an overall similar growth rate over the longer term. No differences in physical production are assumed between the *2 Degrees* and *1.5 Degrees* scenarios.

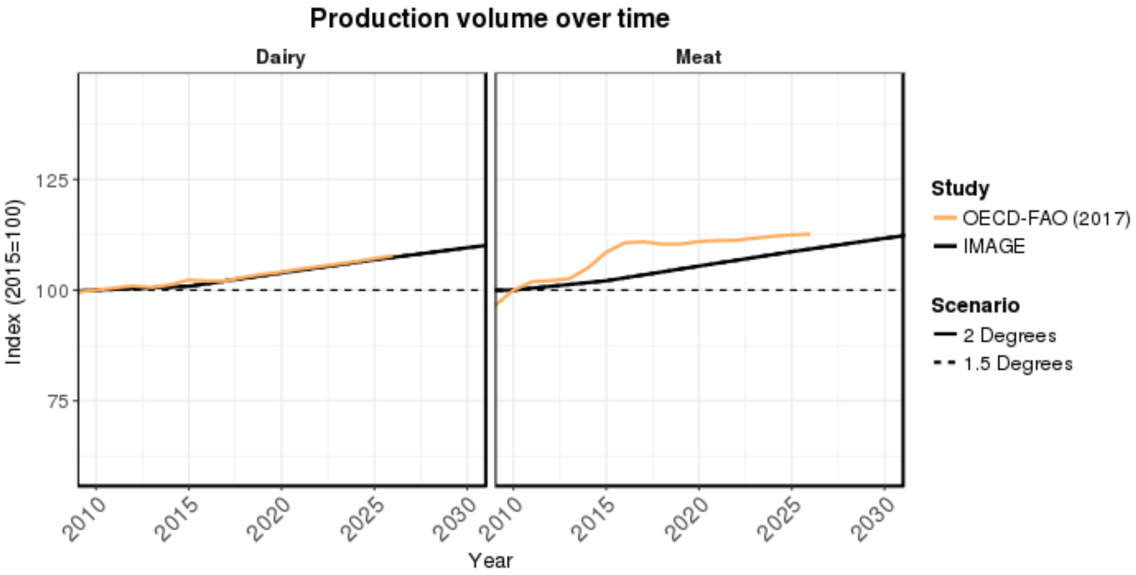


Figure 66. Projected production volume of the meat and dairy sector , Europe (IMAGE and OECD-FAO)

Total final energy consumption projections of the food processing industry differ significantly between the IMAGE scenarios and Schade et al. (2009) (Figure 67). Given the more or less constant energy intensity of the food processing industry over time, a growing demand for food products leads to a growing total final energy demand for food processing. Schade et al. (2009) have refrained from adding a detailed description for the reason of the decline in energy consumption.

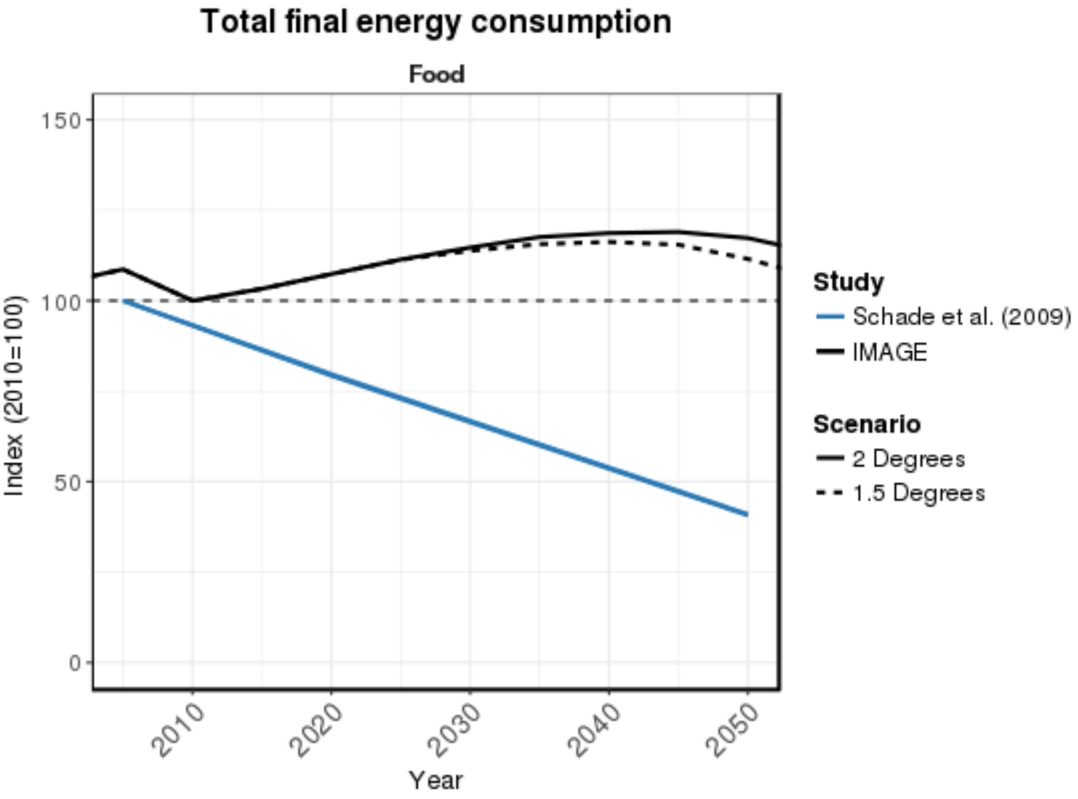


Figure 67. Projected final energy demand of the food processing sector, Europe (IMAGE and Schade et al., 2009).

The IMAGE scenarios shows similar rates of change of CO_2 emissions as two other studies (Figure 68). Our *2 Degrees* scenario show lower reductions than the two existing studies, while in our *1.5 Degrees* scenario CO_2 emissions are reduced more strongly due to a near full switch to biofuels.

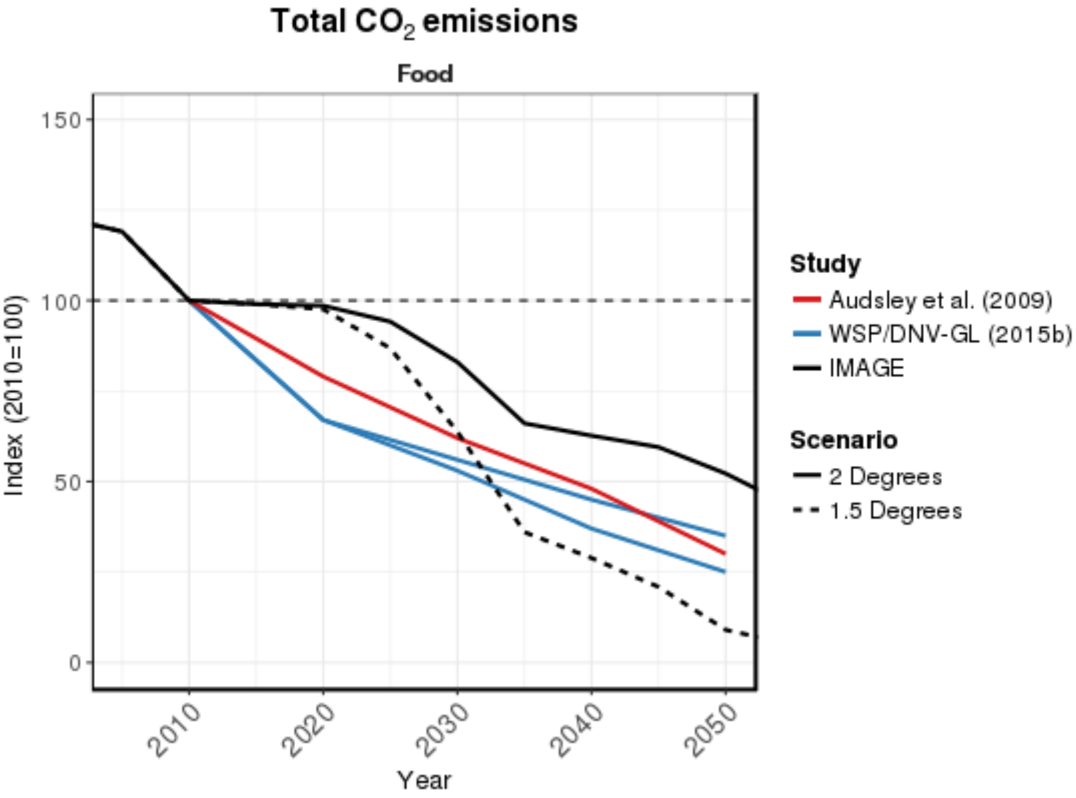


Figure 68. Projected final energy demand of the food processing sector across various studies

7 Discussion and conclusions

In this deliverable a set of long-term strategies to decarbonise four industrial sectors – steel, plastics, paper and meat and dairy – has been assessed. Two modelling approaches have been applied to develop decarbonisation pathways for these manufacturing industries: the top-down integrated assessment model IMAGE and the bottom-up technology-rich model WISEE. Due to methodological differences, two sets of scenarios have been developed and assessed in parallel. One set (IMAGE) is based on a cost-optimal reduction of greenhouse gases over time, regions, and sectors in line with the 2 °C and 1.5 °C climate objectives. The second set (WISEE) reflects on the speed of innovations, investment cycles (existing assets) and possible infrastructure limitations and includes a scenario strongly based on CCS and one on electrification and aspects of a circular economy. The projected pathways have been described in terms of change in production volume, total final energy consumption, and CO_2 emissions to describe the contribution of the considered manufacturing industries and possible transformative pathways to complete the full decarbonisation of the EU economy by 2050.

7.1 Caveats and discussion

Our analysis has shown that there are significant differences between the two sets of scenarios developed by IMAGE and WISEE. These differences are related to the analytical and philosophical differences between the modelling approaches, where IMAGE aims at a cost-optimal way to restrict cumulative emissions system-wide and WISEE aims at total decarbonisation of the sectors in 2050. Next to the methodological and structural differences between these models, several common challenges can be mentioned.

One caveat is that production demand curves based on historical patterns may not approach the expected growth and change of markets, affecting the presented future pathways. The IMAGE model applies statistical modelling to historical data on production volumes per capita and GDP per capita to extract a logistic growth curve that can be extended into the future. Other formulations to correlate demand growth to a system factor are considered in the WISEE model for plastic demand, drawing out a historical relationship between consumption of plastics in Mt per gross value added and the development of gross value added and trade volume. No in-depth research is done on the effect of different relationships in reflecting future growth of product demand. Furthermore, the analysis hints at significant differences in drawing out historical relationships from short temporal trends to longer-term GDP per capita trends. The observed slowing down of demand growth for energy intensive products in Europe and the U.S. since the year 2000 may lower the required decarbonisation efforts by lowering the need for primary production in Europe compared to extrapolations according to long-term trends. Further studies could look into better representations or influences to future product demand.

An important limitation of both IMAGE and WISEE is that they do not model feedback from and to other economic sectors (e.g. transport or residential to the chemical sector). The strategies taken in the scenarios described in this report and also the ones to be developed in WP 4.3 will have feedbacks on the whole economy and on trade flows between world regions. Both IMAGE and WISEE need a wide range of assumptions to cover demand, waste amounts, trade issues, recycling, production technologies and spatial allocations; therefore, the system modelled is too complex for a deep endogenisation of all feedbacks.

7.2 Conclusions

Total net decarbonisation by 2050 is considered feasible under specific future conditions for the four selected manufacturing sectors.

The IMAGE model has outlined potential pathways that are in line with the 2°C and 1.5°C climate objective, allocating the required decarbonisation efforts cost-effectively. In this context, the *2 Degrees* scenario shows a decarbonisation pathway for industry that aligns with the 2°C carbon budget but not with the full decarbonisation objective by 2050. The *1.5 Degrees* scenario, however, exceeds the existing literature on industrial decarbonisation levels and illustrates a future pathway towards a practically full net decarbonisation of the industry as a whole by 2050. This is largely due to the large volume of negative emissions that is projected to become available in the paper & pulp industry, which compensate remaining emissions in the other industries. The WISEE scenario that focuses on electrification indicates that a full decarbonisation of the REINVENT sectors via electrification is feasible in the course of the regular investment cycles, although diffusion will take time until 2030 due to partly low technology-readiness-levels of technologies and due to the high amounts of carbon-free electricity required.

Our results show significant differences between the manufacturing industries and between the models (Table 6). Both the IMAGE and WISEE scenarios show a potential for deep CO_2 emission reductions in the pulp and paper sector. Emissions in the iron and steel industry are significantly reduced, leaving only 1-3% residual emissions by 2050 in the most optimistic scenario. The food processing sector shows sensitivity to the policy stringency, reaching close to full decarbonisation by 2050 under the more ambitious climate policy. The two REINVENT models disagree the most on the potential future pathway of the chemical and petrochemical industry. The IMAGE model depicts reduction rates that cut the sectors' emission levels by half in 2050 while the WISEE model is able to decarbonise the sector, which can be mostly attributed to the availability of carbon capture and storage (CCS) technologies in the WISEE model and biogenic carbon (from black liquor ex pulping) stored in products.

Table 6. Direct emission reductions by 2050 relative to 2015 per industry sector, Europe (%)

MODEL	Chemicals & Petrochemicals	Food Processing	Iron & Steel	Pulp & Paper
WISEE	90 – 125 (CCS-*CIRC*)	-	83 – 99 (CCS-*CIRC*)	100 – 226 (*CIRC*-CCS)
IMAGE	52 – 54 (2°C-1.5°C)	55 – 92 (2°C-1.5°C)	91 – 97 (2°C-1.5°C)	84 – 1056 (2°C-1.5°C)

Strategies on the full decarbonisation of industry require embedment into a broader systems view to remain aligned to the Paris Agreement

In the IMAGE scenarios, deep emission cuts in manufacturing are achieved early-on by a radical adoption of new low-carbon technologies. The bottom-up approach in the WISEE model draws a more conservative picture, showing that the speed of transformative change is more limited due to upfront investments in infrastructure with long planning periods and acceptance issues both in industry and society. As a result, the WISEE model suggests that a complete decarbonisation can be feasible by 2050, but with a cumulative emission budget that is twice as high as the IMAGE scenarios. This result is exclusively due to the development in the steel sector. Potential contributions of higher material efficiency and increased recycling have not been analysed in depth in the scenarios yet.

The potential for emission reduction in the pulp and paper industry is huge, with bioenergy and CCS and electrification as important strategies

The developed decarbonisation pathways towards 2050 vary per manufacturing industry (see Table 7, Table 8, and Table 9). The pulp and paper sector, for instance, is characterised by its high share of bioenergy in power supply, causing the sector to be close to decarbonisation despite expected growth in pulp and paper demand. The pulp and paper industry as presented in the IMAGE model solely represents the greening of steam production as the main area of available transformative change, excluding the option to switch away from steam and towards more alternative processes. In some specific cases this can go hand-in-hand with more innovative constructions, such as retrofitting CCS to existing processes (e.g. CO_2 capture and storage technology connected to the recovery boiler in the chemical pulping processes), opening up potential decarbonisation and electrification venues beyond the sectors' boundaries. Contrary to IMAGE, the WISEE model represents more innovative production processes, including steam generation via electrode boilers and high-temperature heat pumps powered on electricity from renewables. Under high ambitions, the pulp and paper sector shows to gain a more important status in sinking surplus CO_2 emissions by adopting CCS to chemical pulping factories (Table 6). As a result of this, both the IMAGE and WISEE models are able to present more radical decarbonisation pathways than presented in earlier published literature.

In the plastics industry, closing of carbon cycles is a promising route for decarbonisation, next to improving efficiency and CCS

Next to cutting emissions (e.g. via CCS in the incineration of plastic waste and at steam crackers), the closing of carbon cycles (via carbon recycling) is considered an important decarbonisation strategies in the plastics sector. Early on emission reductions can be achieved by shrinking product demand, whereas later emission cuts are achieved by efficiency increase, thorough recycling strategies and a closing of carbon cycles. As plastics manufacturing is far more integrated in other energy intensive value chains than the other sectors, there is a very strong linkage to the refineries as suppliers of (transport) fuel. The direct CO_2 emissions of plastics manufacturing (in particular due to steam cracking) are rather high, but not as relevant for the decarbonisation of the whole system as steel. As such, end-of-life emissions are considered far more relevant in this sector. The WISEE *CIRC* scenario indicates the potential role of this sector as a future carbon sink and shows the feasibility of deep cuts in the mid and long-term using an integrated approach that links circular economy and electrification. The presentation of the chemical and petrochemical industry as included in the IMAGE model shows to have a limited number of decarbonisation options, in the absence CO_2 capture and storage and the limited available biofuel capacity for this sector under stringent climate mitigation ambitions. The main response strategy then involves significant energy demand reductions (Table 8) and demand curtailment of primary material production (Table 9).

Decarbonisation of the steel sector strongly depends on CCS and/or a switch from cokes to hydrogen as a reducing agent

In the IMAGE scenarios, decarbonisation of the steel sector mainly takes place by applying CCS on a large scale. However, in the WISEE scenario that focuses on electrification, hydrogen is expected to play an important role, being used as a reducing agent for the production of direct reduced iron, which can be processed to steel in a blast oxygen furnace (BOF) or an electric arc furnace (EAF).

Table 7. CO_2 storage and shares of energy in total industry final energy use by 2050, Europe (%)

Scenario	Indicator	Unit	Chemicals & Petrochemicals	Food Processing	Iron & Steel	Pulp & Paper
Baseline [IMAGE]	Biofuels	%	18	21	14	69
	Electrification	%	0	36	23	24
	Fossil fuel	%	72	40	63	7
***2 Degrees* [IMAGE]**	Biofuels	%	34	37	15	71
	Electrification	%	1	38	26	25
	Fossil fuel	%	52	25	60	4
	CCS	Mt CO_2 /yr	-	-	78	0
***1.5 Degrees* [IMAGE]**	Biofuels	%	4	54	6	78
	Electrification	%	1	42	35	21
	Fossil fuel	%	82	5	59	0
	CCS	Mt CO_2 /yr	-	-	75	290
CCS [WISEE]	Biofuels	%	-		-	65
	Electrification	%	23		16	35
	Fossil fuel	%	77		84	
	CCS	Mt CO_2 /yr	9		100	30
***CIRC* [WISEE]**	Biofuels	%	71		13	32
	Electrification (incl. hydrogen, but not for material use)	%	29		87	68
	Fossil fuel	%	-		-	-
	CCS	Mt CO_2 /yr	-		-	-

Table 8. Energy demand reductions by 2050 relative to 2015 per industry sector, Europe (%)

MODEL	Chemicals & Petrochemicals	Food Processing	Iron & Steel	Pulp & Paper
WISEE	-13 – 12 (CCS-*CIRC*)	-	-5 – 21 (CCS-*CIRC*)	11 – 35 (*CIRC*-CCS)
IMAGE	5 – 29 (2°C-1.5°C)	-1 – 3 (2°C-1.5°C)	16 – 25 (2°C-1.5°C)	-11 – -32 (2°C-1.5°C)

* negative value indicates an increase

Table 9. Material demand reductions by 2050 relative to 2015 per industry sector, Europe (%)

MODEL	Chemicals & Petrochemicals	Food Processing	Iron & Steel	Pulp & Paper
WISEE	-8 – -6 (CCS-*CIRC*)	-	-	-
IMAGE	5 – 31 (2°C-1.5°C)	-12 – -12 (2°C-1.5°C)	-2 – -2 (2°C-1.5°C)	-22 – -22 (2°C-1.5°C)

* negative value indicates an increase

Biomass is projected to play an important role in the decarbonisation of the food processing sector, but alternatives have not yet been analysed in detail

The IMAGE model shows a large dependency on biofuels and electricity as part of the decarbonisation strategy for the food processing sector. This is partly due to alternative ways of producing thermal energy, for example, by replacing hydrocarbon-fired steam boilers with steam boilers powered by biomass. Some electrification of heat production (heat pump) is assumed to become available after 2030, but the diffusion of this technology is limited to processes with a low temperature heat demand. Other forms of decarbonisation currently not covered in this report, which can have a significant impact on the overall decarbonisation pathway, are dietary change and food waste prevention.

7.3 Future work

Our findings serves as a basis to discuss required decarbonisation efforts in the industry sector, by providing a first indication of potential obstacles and drawing out topics for further research. Based on the caveats and conclusions of our work, we suggest the following routes to improve the scenarios:

- Research on how demand-side measures can contribute to decarbonisation;
- More research on the availability of biofuels, CCS storage sites, electrification of heat, and electrification of processes;
- Research on best practices and technological and social innovations (which will be done in REINVENT by linking future scenarios to be developed in D4.3 and D4.4 with WP3 findings);
- Bottom-up geographical modelling of the take-up of low carbon technologies considering up- and downstream value chain integration at clusters, region-specific CCS storage sites, existing port and pipeline infrastructure, availability of renewable electricity, possible cross-sector synergies (steel & plastics, pulp & plastics);
- System-wide and geographically specific assessment of the potential to use carbon sources (biomass, cement plants, polymer waste) further close carbon loops;
- Material efficiency and service efficiency potentials in the steel and plastics industry.

Diffusion of innovations all along the value chain will have a prominent role in the discussion with stakeholders in D4.3. WP2 and WP3 results will enrich this scenario discussion.

WP4 team was involved in the selection of WP3 case studies to get relevant input to the forthcoming sector scenarios to be co-created with stakeholders in D4.3. Consequently, up-to-date D4.3 planning foresees a joint WP3/WP4 workshop to integrate the insights on the process of taking up innovations into the scenario building. Case studies in WP3 will help to identify possible barriers of uptake with regard to this strategy and an integrated assessment of a deep electrification strategy within the IMAGE framework could be a useful amendment in the course of the forthcoming D4.4.

WISEE showed first order sector-focused electrification scenarios. Cost-efficient deep electrification of the energy system and material supply requires high exchanges of renewable electricity (or electricity-based energy carriers like hydrogen) within Europe but also between densely populated and industrialised regions in Europe and the so called sweet spots for renewable electricity in the world (e.g. Africa, Middle East, Iceland, Canada). One issue in the forthcoming stakeholder discussions in WP4 should be the question if European stakeholders rely on the international cooperation needed to pursue such a strategy.

8 References

Allwood, J.M., Cullen, J.M., Milford, R.L., 2010. Options for Achieving a 50% Cut in Industrial Carbon Emissions by 2050. Environmental Science & Technology 44, 1888-1894.

Audsley, E., Brander, M., Chatterton, J., Murphy-Bo, kern, D., Webster, C., Williams, A., 2009. How low can we go? An assessment of greenhouse gas emissions from the UK food system and the scope to reduce them by 2050., in: WWF-UK (Ed.).

Bellevrat, E., Menanteau, P., 2009. Introducing carbon constraint in the steel sector: ULCOS scenarios and economic modelling, , http://www.ulcos.org/en/docs/seminars/Ref01%20-%20SP9_Bellevrat_Essen.pdf.

Bijl, D.L., Bogaart, P.W., Dekker, S.C., Stehfest, E., de Vries, B.J.M., van Vuuren, D.P., 2017. A physically-based model of long-term food demand. Global Environmental Change 45, 47-62.

Boston Consulting Group/VDEh, 2013. Steel's contribution to a low-carbon Europe 2050.

Broeren, M.L.M., Saygin, D., Patel, M.K., 2014. Forecasting global developments in the basic chemical industry for environmental policy analysis. Energy Policy 64, 273-287.

Carbon Trust, 2011. Industrial Energy Efficiency Accelerator - Guide to the paper sector, https://www.carbontrust.com/media/206496/ctg059-paper-industrial-energy-efficiency.pdf.

CEFIC/Ecofys, 2013. European chemistry for growth - unlocking a competititve, low carbon and energy efficient future.

Clarke, L., Jiang, K., Akimoto, K., Babiker, M., Blanford, G., Fisher-Vanden, K., Hourcade, J.-C., Krey, V., Kriegler, E., Löschel, A., McCollum, D., Paltsev, S., Rose, S., Shukla, P.R., Tavoni, M., van der Zwaan, B.C.C., van Vuuren, D.P., 2014. Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S.Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Daioglou, V., Faaij, A.P.C., Saygin, D., Patel, M.K., Wicke, B., van Vuuren, D.P., 2014. Energy demand and emissions of the non-energy sector. Energy & Environmental Science 7, 482-498.

DECHEMA, 2017. Technology study - Low carbon energy and feedstock for the European chemical industry.

Dellink, R., Chateau, J., Lanzi, E., Magné, B., 2017. Long-term economic growth projections in the Shared Socioeconomic Pathways. Global Environmental Change 42, 200-214.

Dornburg, V., Hermann, B.G., Patel, M.K., 2008. Scenario Projections for Future Market Potentials of Biobased Bulk Chemicals. Environmental Science & Technology 42, 2261-2267.

Engel, E., 1857. Die Productions- und Consumtionsverhältnisse des Königreichs Sachsen. Zeitschrift des statistischen Bureaus des Königlich Sächsischen Ministerium des Inneren 8-9.

Fleiter, T., Fehrenbach, D., Worrell, E., Eichhammer, W., 2012a. Energy efficiency in the German pulp and paper industry–A model-based assessment of saving potentials. Energy 40, 84-99.

Fleiter, T., Fehrenbach, D., Worrell, E., Eichhammer, W., 2012b. Energy efficiency in the German pulp and paper industry - A model-based assessment of saving potentials. Energy 40, 84-99.

Förster, H., Schumacher, K., De Cian, E., HÜBler, M., Keppo, I., Mima, S., Sands, R.D., 2013. European energy efficiency and decarbonization strategies beyound 2020 - a sectoral multi-model decomposition. Climate Change Economics 04, 1340004.

Fragkos, P., Tasios, N., Paroussos, L., Capros, P., Tsani, S., 2017. Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. Energy Policy 100, 216-226.

Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Science Advances 3.

GL, W.P.B.D., 2015a. Industrial decarbonisation & Energy efficiency roadmaps to 2050.

GL, W.P.B.D., 2015b. Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 - Food and Drink.

GL, W.P.B.D., 2015c. Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Pulp and Paper.

Grigoray, O., 2009. Gasification of Black Liquor as a Way to Increase Power Production at Kraft Pulp Mills. Master's thesis. Lappeenranta University of Technology.

Große, R., Binder, C., Wöll, S., Geyer, R., Robbi, S., 2017. 2017 Techno-economics for larger heating and cooling technologies, in: European Commission, J.R.C.J. (Ed.), http://data.europa.eu/89h/jrc-etri-techno-economics-larger-heating-cooling-technologies-2017.

Group/VDEh, B.C., 2013. Steel's contribution to a low-carbon Europe 2050.

Heaps, C., Erickson, P., Kartha, S., Kemp-Benedict, E., 2009. Europe's Share of the Climate Challenge - Domestic Actions and International Obligations to Protect the Planet, http://sei-us.org/Publications_PDF/SEI-EuropeShareOfClimateChallenge-09.pdf.

ICF Consulting Ltd, 2015. Study on Energy Efficiency and Energy Saving Potential in Industry from possible Policy Mechanisms.

IEA, 2009. CHEMICAL AND PETROCHEMICAL SECTOR. Potential of best practice technology and other measures for improving energy efficiency.

Järvinen, J., Lamberg, J.-A., Nokelainen, T., Tikkanen, H., 2012. Global Demand for Paper Products: 2006–2050, in: Lamberg, J.-A., Ojala, J., Peltoniemi, M., Särkkä, T. (Eds.), The Evolution of Global Paper Industry 1800¬–2050: A Comparative Analysis. Springer Netherlands, Dordrecht, pp. 307-343.

JRC, 2015. Best Available Techniques (BAT) Reference Document for the Production of Pulp, Paper and Board, Seville.

JRC, 2017. Best Available Techniques (BAT) Reference Document in the Large Volume Organic Chemical Industry.

JRC/PBL, 2014. Emission Database for Global Atmospheric Research (EDGAR) version 4.2FT2012, http://edgar.jrc.ec.europa.eu/overview.php. European Commission, Joint Research Centre (JRC) / PBL Netherlands Environmental Assessment Agency.

Kc, S., Lutz, W., 2017. The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. Global Environmental Change 42, 181-192.

Lechtenböhmer, S., Schneider, C., Yetano Roche, M., Höller, S., 2015. Re-Industrialisation and Low-Carbon Economy—Can They Go Together? Results from Stakeholder-Based Scenarios for Energy-Intensive Industries in the German State of North Rhine Westphalia. Energies 8, 11404-11429.

Meinshausen, M., Raper, S.C.B., Wigley, T.M.L., 2011. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6 - Part 1: Model description and calibration. Atmospheric Chemistry and Physics 11, 1417-1456.

Methanol Institute, 1999-2003. Global Methanol Capacity, Brussels.

Milford, R.L., Pauliuk, S., Allwood, J.M., Müller, D.B., 2013. The roles of energy and material efficiency in meeting steel industry CO2 targets. Environmental science & technology 47, 3455-3462.

Naegler, T., Simon, S., Klein, M., Gils, H.C., 2015. Quantification of the European industrial heat demand by branch and temperature level. International Journal of Energy Research 39, 2019-2030.

Neelis, M.L., Patel, M.K., 2006. Long-term production, energy consumption and CO2 emission scenarios for the worldwide iron and steel industry, Utrecht University, Copernicus Institute, Department of Science, Technology and Society, Report NWS-E-180.

O’Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Global Environmental Change 42, 169-180.

OECD/FAO, 2017. OECD-FAO Agricultural Outlook 2017-2026, https://stats.oecd.org/Index.aspx?DataSetCode=HIGH_AGLINK_2017.

OECD/IEA, 2009. Energy Technology Transitions for Industry, https://www.iea.org/publications/freepublications/publication/industry2009.pdf.

OECD/IEA, 2016a. Energy efficiency market report 2016.

OECD/IEA, 2016b. Energy Technology Perspectives - Towards Sustainable Urban Energy Systems.

OECD/IEA, 2017a. Energy Technology Perspectives - catalysing energy technology transformations.

OECD/IEA, 2017b. World Energy Balances 2017, in: IEA (Ed.), https://www.iea.org/publications/freepublications/publication/world-energy-balances---2017-edition---overview.html.

OGJ, 1997-2012a. International Survey of Ethylene from Steam Crackers. Oil and Gas Journal.

OGJ, 1997-2012b. Worldwide Refineries. Penwell Corporation, Houston, Texas.

Onarheim, K., Santos, S., Kangas, P., Hankalin, V., 2017. Performance and cost of CCS in the pulp and paper industry part 2: Economic feasibility of amine-based post-combustion CO2 capture. International Journal of Greenhouse Gas Control 66, 60-75.

Pardo, N., Moya, J.A., Vatopoulos, K., 2012. Prospective scenarios on energy efficiency and CO2 emissions in the EU iron & steel industry, Publications Office of the European Union.

Ramirez Ramirez, C.A., 2005. Monitoring energy efficiency in the food industry, https://dspace.library.uu.nl/bitstream/handle/1874/20680/NWS-E-2005-66.pdf?sequence=1.

Rehfeldt, M., Fleiter, T., Toro, F., 2018. A bottom-up estimation of the heating and cooling demand in European industry. Energy Efficiency 11, 1057-1082.

Remus, R., Aguado Monsonet, M.A., Roudier, S., Delgado Sancho, L., 2013. Best Available Techniques (BAT) Reference Document for Iron and Steel Production JRC.

Ren, T., 2009. Petrochemicals from Oil, Natural Gas, Coal and Biomass: Energy Use, Economics and Innovation (PhD thesis).

Riahi, K., van Vuuren, D.P., Kriegler, E., Edmonds, J., O'Neill, B.C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J.C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., Ebi, K., Hasegawa, T., Havlik, P., Humpenöder, F., Da Silva, L.A., Smith, S., Stehfest, E., Bosetti, V., Eom, J., Gernaat, D., Masui, T., Rogelj, J., Strefler, J., Drouet, L., Krey, V., Luderer, G., Harmsen, M., Takahashi, K., Baumstark, L., Doelman, J.C., Kainuma, M., Klimont, Z., Marangoni, G., Lotze-Campen, H., Obersteiner, M., Tabeau, A., Tavoni, M., 2017. The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. Global Environmental Change 42, 153-168.

Roorda, C., 2006. Inclusion of production, energy use and value added for steel, cement and paper in the TIMER energy demand module. https://dspace.library.uu.nl/bitstream/handle/1874/21828/NWS-E-2006-179.pdf?sequence=1&isAllowed=y.

Saygin, D., 2012. Assessing industrial energy use and CO2 emissions – opportunities for energy efficienciy, biomass and CCS (PhD thesis).

Schade, W., Jochem, E., Barker, T., Catenazzi, G., Eichhammer, W., Fleiter, T., Held, A., Helfrich, N., Jakob, M., Criqui, P., Mima, S., Quandt, L., Peters, A., Ragwitz, M., Reiter, U., Reitze, F., Schelhaas, M., Scrieciu, S., Turton, H., 2009. ADAM 2-degree scenario for Europe – policies and impacts. Deliverable D-M1.3 of ADAM (Adaptation and Mitigation Strategies: Supporting European Climate Policy). Project co-funded by European Commission 6th RTD Programme. Karlsruhe, Germany.

Schneider, C., Lechtenboehmer, S., 2016. Industrial site energy integration – the sleeping giant of energy efficiency? Identifying site specific potentials for vertical integrated production at the example of German steel production, eceee Industrial Summer Study proceedings : Industrial Efficiency 2016. 12-14 September 2016, Stockholm.

Schneider, C., Friege, J., Samadi, S., Lechtenböhmer, S., Van Sluisveld, M.A.E., Hof, A.F., van Vuuren, D.P., 2017. Deliverable 4.1 - Existing visions and scenarios, https://www.reinvent-project.eu/s/D41-Existing-visions-and-scenarios.pdf.

Schneider, C., Lechtenboehmer, S., Xia, C., 2018. Scenario analyses on a conversion of the European petrochemical industry to power to plastics. ENCO2RE LTP report on Deliverables 2 & 3, Wuppertal.

Stehfest, E., Bouwman, L., Van Vuuren, D.P., Den Elzen, M.G.J., Eickhout, B., Kabat, P., 2009. Climate benefits of changing diet. Climatic Change 95, 83-102.

Stehfest, E., van Vuuren, D.P., Bouwman, A.F., Kram, T., Alkemade, R., Bakkenes, M., Biemans, H., Bouwman, A., den Elzen, M.G.J., Jansen, J., Lucas, P., Van Minnen, J., Müller, M., Prins, A., 2014. Integrated Assessment of Global Environmental Change with IMAGE 3.0. Model description and policy applications, the Hague: PBL Netherlands Environmental Assessment Agency, http://www.pbl.nl/en/publications/integrated-assessment-of-global-environmental-change-with-IMAGE-3.0.

USGS, 1996-2012. Minerals Yearbook: Nitrogen. US Geological Survey, Reston VA, USA.

Van Ruijven, B.J., Van Vuuren, D.P., Boskaljon, W., Neelis, M.L., Saygin, D., Patel, M.K., 2016. Long-term model-based projections of energy use and CO 2 emissions from the global steel and cement industries. Resources, Conservation and Recycling 112, 15-36.

van Sluisveld, M.A.E., Martínez, S.H., Daioglou, V., van Vuuren, D.P., 2016. Exploring the implications of lifestyle change in 2 °C mitigation scenarios using the IMAGE integrated assessment model. Technological Forecasting and Social Change 102, 309-319.

van Vuuren, D.P., Stehfest, E., Gernaat, D., van den Berg, M., Bijl, D.L., de Boer, H.S., Daioglou, V., Doelman, J.C., Edelenbosch, O.Y., Harmsen, M., Hof, A.F., van Sluisveld, M.A.E., 2018. Alternative pathways to the 1.5 °C target reduce the need for negative emission technologies. Nature Climate Change in press. DOI: 10.1038/s41558-018-0119-8.

VLEEM, 2005. VLEEM 2 Final Report EC/DG Research - Contract ENG1-CT 2002-00645.

Wang, L., 2014. Energy efficiency technologies for sustainable food processing. Energy Efficiency 7, 791-810.

World Bank, 2010. GDP, PPP (constant 2005 international $). International Comparison Program Database.

WSP Parsons Brunckerhoff / DNV GL, 2015. Industrial Decarbonisation & Energy Efficiency Roadmaps to 2050 – Pulp and Paper.