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Existing visions and scenarios

Deliverable 4.1

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1 Introduction

1.1 Motivation

Scenarios are analytical tools used to explore possible future developments and study the diversity in perspective on long-term systemic change. Task 4.1 of the REINVENT project uses a scenario meta-analysis to compile the views and assumptions on decarbonisation strategies for industry. As such, the meta-analysis provides a stocktake of considered transformation pathways by industry stakeholders and academia.

The meta-analysis intends to provide input to the design of new scenario storylines for Task 4.2, which lays the foundation for the planned stakeholders dialogues in Task 4.3.

1.2 REINVENT focus; selection of sectors

The REINVENT project addresses the decarbonisation potential in four industrial sectors with current and expected future high levels of energy use and/or carbon intensity, but which are still relatively unexplored. The four sectors taken into consideration are:

1. Steel sector:

The *steel* sector comprises a value chain that covers mineral extraction, iron and steel making, steel processing, steel use in other manufacturing industries like construction or transport equipment, and also the recycling industry. However, only “iron and steel making” and “steel processing” can be identified as clear statistical aggregates. Other activities relate to the iron and steel sector, but also to other sectors such as plastics or machinery. Iron and steel making is from a meta-level rather homogenous with regard to the products and to the used technologies. It is by far the most energy intensive part of the steel value chain, where product volumes, technology use, energy demand and emissions are well reported. Therefore, it can be analysed very well. In our selection of scenarios, we concentrated on studies delivering a clear view on that core part of the value chain.

2. Plastics sector:

The *plastics* sector value chain can be defined as the material flows from oil extraction to plastic products and recycling. However, the value chain is far more complex than the one for steel as it includes many by-products which cover a wide range of sectors. In fact, the same production technologies are attributed to the refinery sector and the basic chemicals sector, depending on the main activity of the operating company. Production technologies more downstream are attributed either to the basic chemical industry or the plastics and rubber industries. As a result, literature shows varying levels of detail on the plastics industry, and we have included both studies that cover the chemical sector as a whole and studies specifically on plastics.

3. Paper sector:

The paper sector covers another crucial basic product of the industrial metabolism. The paper sector relies on biomass and is therefore connected to land use. The actual paper making process can be analysed quite well, although the statistical aggregation with the very low energy intensive printing industry is problematic. In this report, scenarios on paper and pulp making are included.

4. Meat and dairy:

Finally, the REINVENT project addresses the meat and dairy sectors, covering sub-sectors such as agriculture, food processing (i.e. slaughterhouses and dairy plants) as well as retail. The agricultural sub-sector is very greenhouse gas (GHG) intensive, the food-processing sub-sector is not very energy intensive compared to the other three industrial sectors analysed within the REINVENT project, and the retail sub-sector is quite electricity-intensive with regard to refrigeration needs and material intensive with regard to packaging (with links to the other three sectors).

As the above four sectors do not always represent the statistical aggregates as included in formal energy and GHG reporting, which are the most relevant data sources for modelling and scenarios, the current analysis will not in all cases use exactly the same boundaries of the REINVENT sectors.

2 Data and Methodology

The meta-analysis of scenarios comprised four steps: 1) Development of a scenario analysis tool, 2) Selection of the scenario studies, 3) Data extraction from the scenario studies, 4) Data processing presentation of the results.

1) A scenario analysis tool was developed to organize and standardize the data collection process. The analysis tool is structured as depicted in the following table.

Table 1 - Structure of scenario analysis tool

Section	Parameter
General information	Name of study and scenario; name and type of model used; regional scope and differentiation; base year and scenario horizon
Information on each sector	Depth of value chain analysed, Gross Value Added (GVA) development; methodology used to deduce production volumes; technological strategies included; primary and final energy demand; electricity use; GHG emissions
Iron and steel industry	Production volume of crude steel; share of scrap steel
Pulp and paper industry	Production volume of pulp; production volume of paper and board
Plastics industry	Production volume of olefins; production volume of polymers; share of mechanical recycling in polymer supply

2) In cooperation with WP1, Task1.1, a literature screening was conducted to draw out relevant decarbonisation strategies for individual industry sectors. Given the global commitment to limit global warming to below 2°C (UN, 2015), the analysis assumes uniformity and therefore scalability of decarbonisation strategies. As a result, and a means to boost the number of perspectives, we draw insights from studies covering all spatial scales (global, EU and national level).

   To warrant representativeness in decarbonisation strategies, we selected studies that (1) are relatively recently published (2009 or later), (2) include a time horizon of up to 2050 and (3) include quantitative detail with regard to their respective considered long-term considerations. An overview on the scenario studies considered is part of the sections that presents the results of the analysis (Section 4).

3) The data acquisition from the scenario studies was split among the participating institutions. Required data (see Table 1) was extracted from the text, tables, and (if necessary) read off graphs from the scenario studies and entered into a spreadsheet for further processing.

4) A number of measures were carried out to improve the comparability and thus usability of the data acquired. At first, the data was converted to equal units. Next, in an iterative process, a number of different presentation options were tested before a decision was made for a certain way of presenting the data. Finally, due to differing base and target years in the studies, we decided to present the developments of the different parameters in a "percentage change per year" metric to allow easier comparison of the parameters.

3 Current trends and developments

This section describes the current trends in the four sectors and the industry as a whole, providing context to the developments in the scenarios.

3.1 Gross value added and energy intensity

As stated before the four REINVENT sectors do not fully represent the statistical aggregates as included in the macroeconomic accounts and in formal energy and GHG statistics. The relevant statistical aggregates in the following figures derived from national accounts are (i) metal industry (which covers the REINVENT steel sector), (ii) base chemicals and (iii) rubber and plastic products (both covering the REINVENT plastics sector), (iv) paper and printing (covering the REINVENT paper sector), and (v) food, beverages and tobacco (covering the REINVENT meat and dairy sector).

Figure 1 shows the development of the GVA of the statistical aggregates from 2000 to 2011 (which is the latest year with a full report for all EU 28 Member States). The GVA of the base chemicals industry has shown the fastest increase, followed by rubber and plastics. The increase of the GVA of the other three sectors are lower than the average of the manufacturing industry, with the metal industry even showing a decline. While Figure 1 suggests that our four REINVENT sectors comprise more than one quarter of total industrial GVA, this is in fact less, as i) the metal industry also comprises non-ferrous metals (like aluminium), ii) base chemicals cover more than only plastic products, and iii) meat and dairy is only a small part of the food, beverage and tobacco sector.

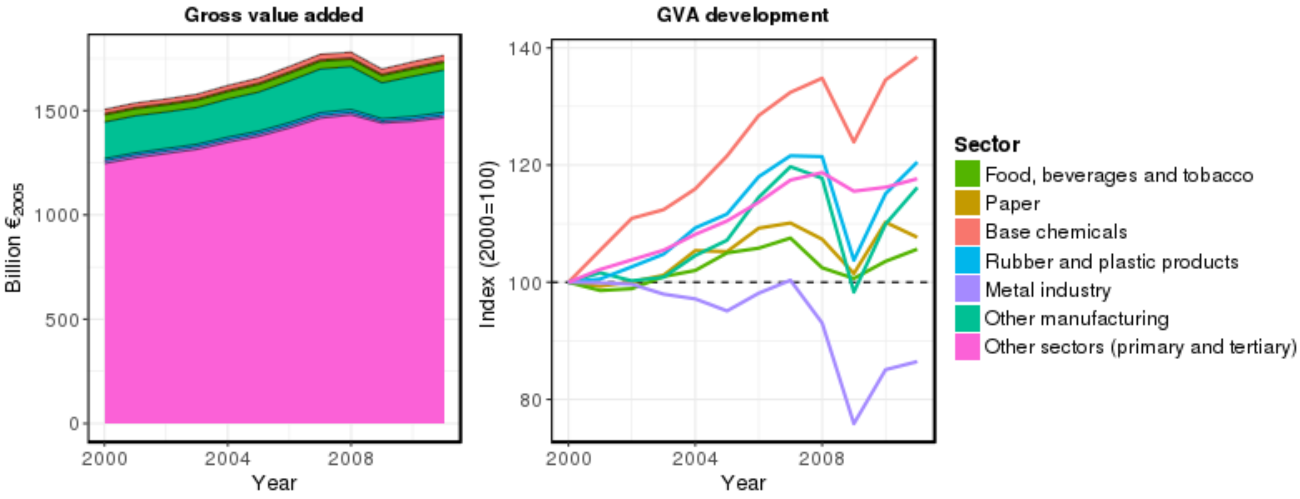

Figure 1 - Gross value added of the REINVENT sectors and the total manufacturing sector in the EU-28. Own graph based on Eurostat data.

Figure 2 shows the historical energy efficiency performance of the sectors, expressed as the energy needed to produce one unit of GVA[1]. The left panel shows that the levels of energy intensity differ strongly between the sectors, with basic metals having an energy intensity which is about eight times higher than the food, beverages, and tobacco industry. The right panel compares the development in energy intensity between the sectors, showing that the paper industry showed hardly any improvement over the last decade, while the other REINVENT sectors showed improvements of about

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[1] The time series of GVA related energy intensities do not report on technical efficiency performance (indicated by the units of energy used to produce one physical unit of product). GVA per physical unit of product differs over time according to the development of product market prices and factor prices.

1% p.a. The rest of the manufacturing industry showed larger improvements, but this is not a suitable reference as it may be attributed to intra-sectoral changes in favour of non-energy intensive industries.

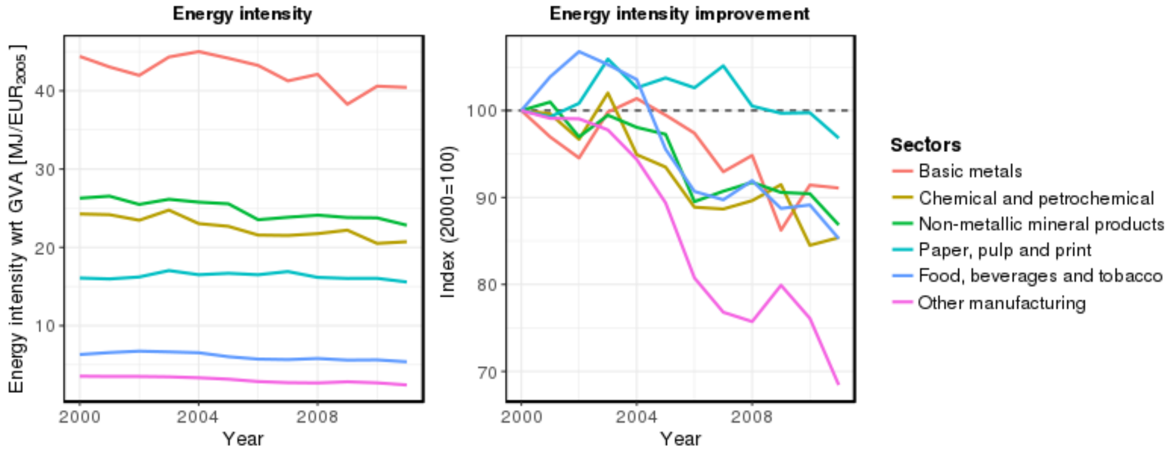

Figure 2 - Energy intensity of different industry sectors in the EU-28 in regard to real GVA (absolute values and index development from 2000-2011). Own graph based on Eurostat data.

3.2 Total Final Energy Consumption

Absolute industrial energy demand in Europe (here EU-27) has decreased from about 15 EJ throughout the 70s to about 11.5 EJ currently, thereby using about 25% of total final energy consumption by 2015. Currently, the chemical sector (20.4%), non-metallic minerals (13.1%), paper production (12.8%), food production (11.5%), and iron and steel (11.4%) take the largest shares in total industrial energy demand (Figure 3, OECD/IEA, 2017).

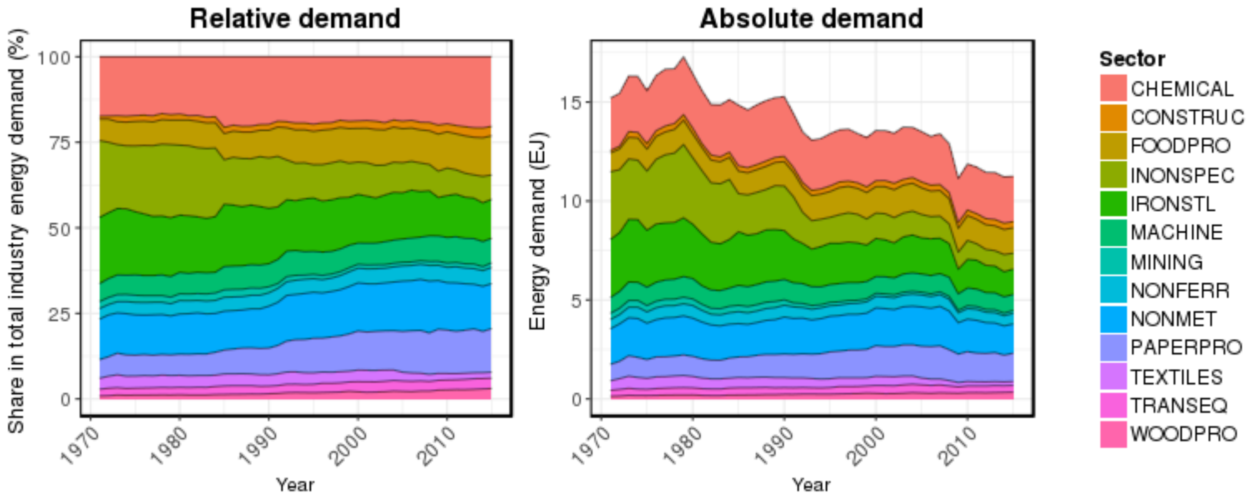

Figure 3 – (left) Share in energy demand per sector in total industry energy demand for Europe (EU27) and (right) absolute total energy demand (in EJ).

Note: Industry entails sections B-E of ISIC Rev. 4 or NACE Rev. 2 classifications. Edited from OECD/IEA (2017). Sector abbreviations are further explained in Annex I.

Nearly half of the industrial processes depended on fossil resources (mainly gas) in 2015, another 35% on electricity, 18% on renewable resources (liquid and solid biomass from primary or secondary sources (waste)), and the remaining on heat (8%) (Figure 5). The share of coal and heavy oil has decreased strongly over the last 20 years, with increasing shares of renewables and gas.

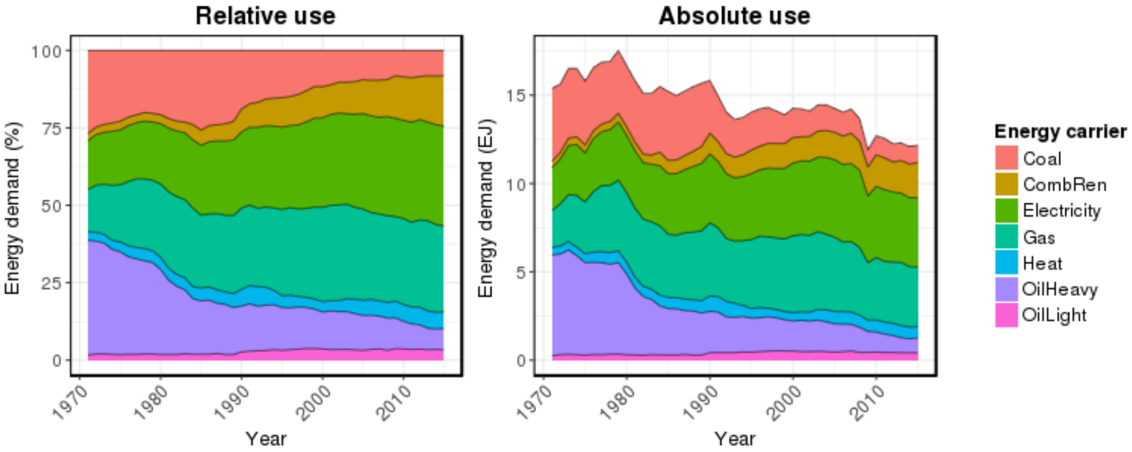

Figure 4 – Share per energy carrier in total sectoral energy consumption in Europe (EU27) (left) and total energy use per energy carrier (in EJ) (right).

Note: Industry entails sections B-E of ISIC Rev. 4 or NACE Rev. 2 classifications. Edited from OECD/IEA (2017)

3.3 Total emissions by industry

European industrial GHG emissions have fallen from 500 Mt CO_2-eq during the 1990's to less than 400 Mt CO_2-eq in 2015 (Figure 6). The largest contributions are from the mineral (cement, glass, lime, etc.), chemical and metal industries.

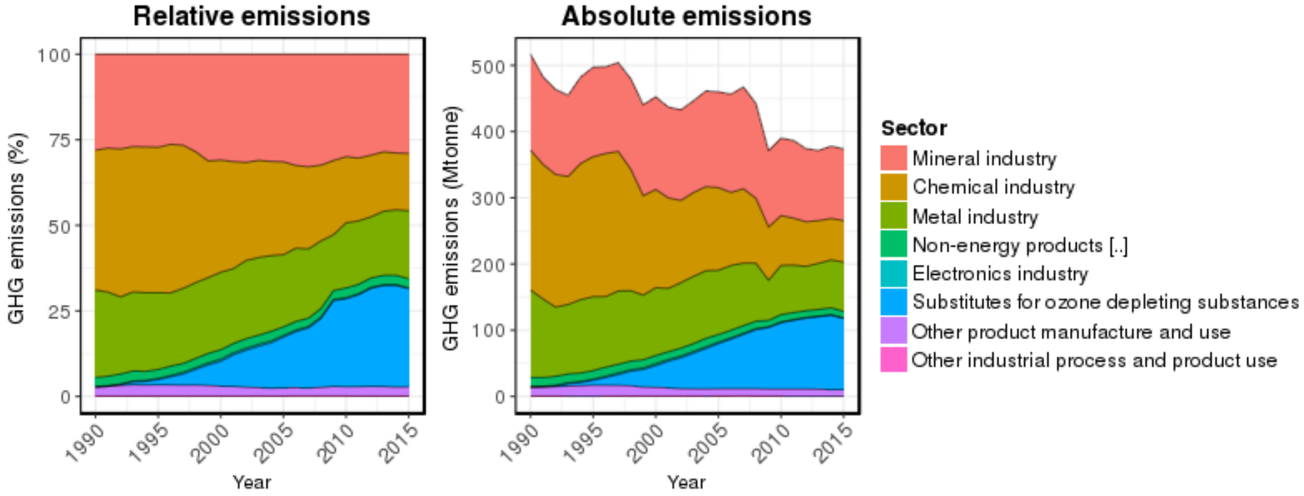

Figure 5 - (left) relative GHG emissions per emission source for EU28 and (right) total GHG emissions (Mtonne).

Note: Emission sources entail all industry sectors (CRF2-A:G). Edited from Eurostat (2014).

4 Scenarios

4.1 Type of models used in our assessment

Van Beeck (2000) distinguishes top-down ("economic" or econometric) from bottom-up ("engineering") approaches. The studies covering the total energy system (with industry as one sub-system) combine a variety of different quantitative assessment frameworks, applying different representations within each considered modelling framework. Studies based on macroeconomic models, for example, simulate the impacts of human activity on the broader economy. Such studies contain a detailed representation of the economy, and are more capable of representing economic structural change than adopting technology-explicit decarbonisation strategies (Kriegler et al., 2015; van Vuuren et al., 2009). Energy system or engineering models, on the other hand, have a more detailed representation of systems and their associated (technical) processes. Such models focus more on implementation of energy efficiency by altering the technical and/or economic characteristics of specific technologies (Förster et al., 2013). Most of the models used in the analysed *sector scenario studies* focussing on one industry sector are bottom-up models, i.e. they have a rather technical representation of the system examined. This finding, however, can be related to the selection process. Only sector studies were selected that gave insights to physical production and technology options in the sector. These are parameters economic top-down models commonly do not cover.

Another model characteristic is the degree of *endogenisation* showing the ability of the model to simulate decisions. When applying an energy model with a low degree of endogenisation, the modeller (or some expert group) takes decisions on technology choice via assumption on market shares. In a model with high degree of endogenisation, investment and/or dispatch decisions are taken by a modelling procedure, e.g. an optimisation tool or a multinominal logit function.

A further dimension is the scenario approach. Here we can differentiate between explorative and target orientated scenarios. Explorative scenarios examine the impacts of a decision (e.g. the GHG reduction by the application of a technology) whereas target orientated scenarios set a specific constraint (i.e. some GHG reduction target) and explore pathways to respect the constraint. Technology potential studies belong to the first category whereas most of the climate policy consulting studies in the international (IPCC) context rely on models of the latter category.

The spatial detail also differs between the studies. Studies on a national or sectoral level allow more spatially explicit detail within the boundaries of the assessment framework than global or world regional models. For example, dedicated engineering models are associated with more detailed representations of sectors, processes and technologies, and are therefore more explicit in strategic depictions of technological change. As these models generally do not assess the associated implications in a broader spatial or systemic context, they are sometimes coupled to integrated assessment models (IAMs) in a broader modelling framework to balance explicitness with broader trends (e.g. Schade et al. 2009). IAMs are generally used to study the implications of human activity on global environmental problems such as climate change or biodiversity. They focus on broader system change and include less detail on lower spatial scales, as they aim at showing the broader trends in development over time. IAMs study both the impact of exploratory and target-oriented scenarios, with a stronger focus on the latter kind of scenarios. They allocate GHG reductions between the sectors endogenously to reach an overall system GHG target. IAMs may optimize towards a long-term objective (minimisation of costs) via perfect foresight (backcasting), may use myopic foresight for an intertemporal optimisation or use a simulation approach (without perfect foresight).

Hybrid modelling systems may combine a variety of different models with different representations, but models with only a soft link between industry sector and energy supply system do not allow for total system optimisation.

The WSP sector studies (include references) are a special case. WSP takes a stakeholder-orientated scenario building approach and does not use a model, but rather a scenario tool aggregating and accounting stakeholder decisions on possible market shares of technologies. This kind of methodology is broadly used in the business consultancy sector but is less common in scientific studies on the energy sector as any relevant interdependencies between technologies need to be implicitly taken into account by the experts.

4.2 Total industry sector analysis

4.2.1 Study selection

The bulk of long-term assessment studies focus on the decarbonisation of the power sector as the leading and early-on decarbonisation strategy, which through electrification is an indirect mitigation strategy for the industry sector (Clarke et al., 2014). Most long-term integrative assessment studies are less detailed about industrial decarbonisation strategies and describe response strategies in more aggregate indicators. Only a more limited set of studies have assessed industrial decarbonisation strategies in Europe more explicitly (see Table 2).

Table 2 - Overview of prospective studies focussing on decarbonisation strategies for industry in Europe

Source	Reference scenario	Decarbonisation scenario(s)	Outlook	Assessment framework	Strategies considered for the industry sector in decarbonisation scenarios
OECD/IEA (2017a)	Includes current and announced policies. Temperature increase of 2.7°C by 2100.	2°C („2DS“) <2°C („B2DS“)	2060	Interlinked model framework (technology-rich sector models)	Fuel switching Energy efficiency Deployment of BAT CCS Material efficiency (yield improvement, recycling, product life extension) Feedstock substitution
Förster et al. (2013)	EU 2020 objectives met, and 40% GHG reductions by 2050 (Temperature increase of ~4°C by 2100)	-80% of total GHG emissions by 2050 (wrt 1990)	2050	Macroeconomic models (computable general equilibrium and optimal growth), Energy system models (optimisation and simulation) Hybrid forms of macroeconomic models and bottom-up system models.	Energy efficiency improvements
Schade et al. (2009)	Temperature increase of 4°C by 2100	2°C („450 ppm“) <2°C („400 ppm“)	2050	Interlinked hybrid model system (8 models with a bottom-up sectoral perspective, 2 with a macro-economic perspective)	Fuel switching Energy efficiency Deployment of BAT CCS Material efficiency (yield improvement, recycling, product life extension) Feedstock substitution

Fragkos et al. (2017)	EU current policies (2020 framework)	-80% of total GHG emissions by 2050 (wrt 1990)	2050	Hybrid modelling framework coupling an energy system model (PRIMES) with a macroeconomic system model (GEM-E3)	Fuel switching Energy efficiency CCS

The studies represent a wide range in future perspectives (see Figure 6) as a result of a large degree of heterogeneity among the studies. This heterogeneity results from differences between the studies with regard to the modelling focus and the modelling procedures as described in the Section 4.1. But the studies also cover different areas of interest in terms of geographical, sectoral and temporal scale. Given differences in the representations, included response behaviours and the scopes and foci of the included studies, we standardized the available data to the provided reference scenario and the latest reported historical value (which varies by study). In the following we compare a limited set of common indicators found in most of the studies, i.e. total final energy consumption in industry and total direct CO_2 emissions.

4.2.2 Future decarbonisation trends

Direct and indirect (CO_2) emissions reductions:

The studies taken into consideration project decreasing direct industrial emissions under baseline assumptions, with one exception in the Förster et al. (2017) study (VTT-TIMES model). Overall, they project a 23% increase to a 45% reduction in direct industrial CO_2 emissions by 2050 compared to the base year (which varies between 2005 and 2014). The OECD/IEA (2017) study shows lower baseline emissions compared to the other analysed studies.

Under decarbonisation policy considerations, the studies show trajectories leading to a 40%-85% emission reduction in the industry sector by 2050 compared to baseline (40% to 80%) and base year levels (40% to 85%). The ensemble of studies show different pathways in terms of immediacy – showing trajectories with immediate emission reductions and trajectories that postpone significant emission reductions until after 2030.

Total Final Energy Consumption

The estimated levels of future European industrial final energy consumption diverge among the climate protection scenarios. In some models, the industrial energy demand is expected to increase towards mid-century, whereas other studies project a decrease in total final energy consumption. The median value of all climate protection scenarios in the studies shows a decrease in final energy demand of about 25% in 2050 relative to the base year of each separate study, but the total range is from a 75% decrease to a 25% increase.

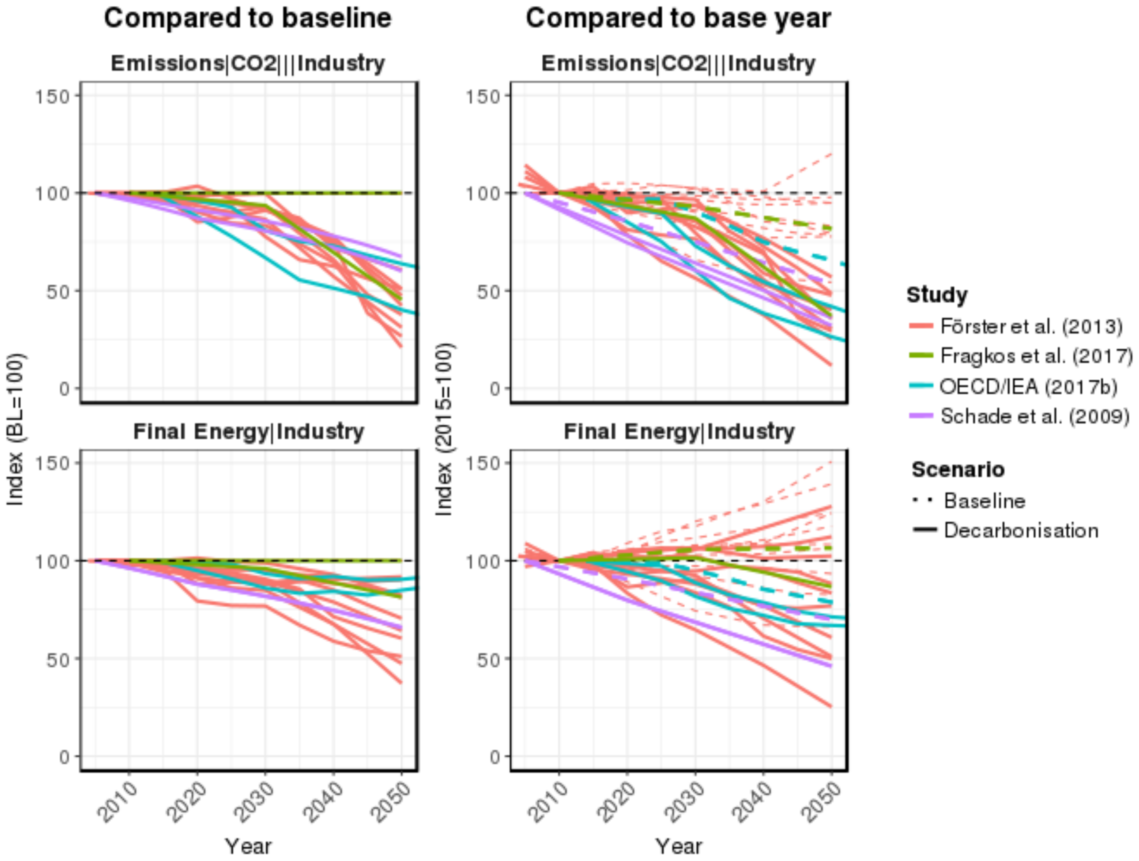

Figure 6 - Depicted decarbonisation trends on thee indicators (Förster et al., 2012; OECD/IEA, 2017).

Note: Base years included are 2005 (Schade et al., 2009), 2010 (Förster et al., 2013) and 2015 (OECD/IEA, 2017).

4.2.3 Comparative assessment of transition strategies

Due to limited data provision, a more in-depth analysis could be performed only for a more limited set of scenarios (particularly Förster et al. 2013). Here we shortly consider the change in industrial energy productivity (energy unit per value added[2]) and industrial emissions intensity (emissions per unit of energy used). However, forward-looking projections of energy productivity are only reported in Förster et al. (2013) (see Figure 7). We compare both, the decades' average annual reduction rate [linear rate] and the decades' compound average annual reduction rate [exponential reduction].

Most of the industrial improvement depictions in Förster et al. (2013) assume energy efficiency improvements in the short-term (until 2030) for both the policy baseline and decarbonisation scenarios. The average annual decline in energy demand is largest early on in the century for both scenarios, but the relative annual reductions are higher in decarbonisation scenarios later on in the century. Until 2030, annual efficiency improvements of about -0.7% to 2% (compound rate, baseline) or 1.7% to 4% (compound rate, decarbonisation) are projected in Förster et al. (2013), while this rate increases to 2% to 5% under decarbonisation assumptions in the period from 2030 to 2050. This equates to a decades-long sustained energy efficiency improvement of 1 to 3 times the current rate, which has only been observed incidentally in emerging economies to date (e.g. China, with a 5.6% rate in 2015 (OECD/IEA, 2016)).

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[2] Förster et al. (2013) shows gross value added values, which are more or less insensitive to the type of climate policy assumed (reflective of exogenous trend).

The emission intensity improvements in decarbonisation strategies have a smaller contribution in the short term (ranging from 0%-1%) than later in the century (0.2% to 5%, for which compound rates are higher than linear rates over a sustained period). The rates of change in Förster et al. (2013) are broadly in agreement with the other studies (Schade et al. 2009, OECD/IEA 2017b, Fragkos et al. 2007). This reflects the fact that only in a policy scenario with stringent climate policy, and only after 2030, more aggressive emission efficiency measures are adopted. The scenarios in Figure 8 project emissions intensities of between 40-60 g CO_2/kJ (Förster et al., 2013) by 2050. These are higher than in other European studies, depicting carbon intensities of 13-20 g CO_2/kJ (OECD/IEA, 2017), 32-36 g CO_2/kJ (Schade et al., 2009) and 32 g CO_2/kJ (Fragkos et al., 2017) for the same year.

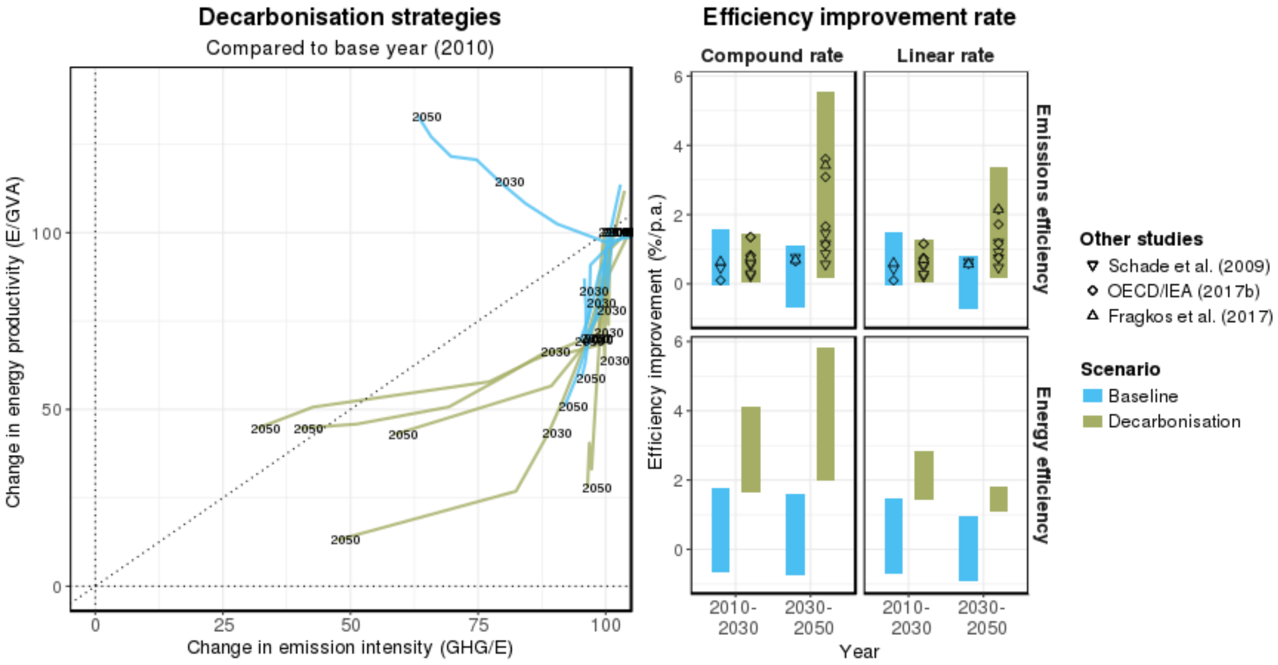

Figure 7 - Energy productivity and emission intensity improvements in the industry sector for all participating models over time in Förster et al. (2013).

Note: The carbon intensity improvement rates in Förster et al. (2013) are plotted against the rates of change as considered in other studies.

4.3 Steel sector

4.3.1 Model and scenario categorisation

In our analysis we examined 15 scenario studies covering the steel sector explicitly. When developing the three *Energy Technology Perspectives* reports of 2015, 2016 and 2017 the IEA used the same model (in the following referred to as "IEA17"). Table 3 shows that six of the models cover the global steel industry, four refer to the EU-27 and three are models covering individual countries or sub-region of the EU.

Table 3 - Overview on energy and GHG models covering the steel industry

Study	Region	Model type					scenario approach	energy system integration	modelling procedure	Source
		Bottom-up		Top-down		Hybrid				
		endog. low	endog. high	endog. low	endog. high	endog. high				
ALL10	World			x			GHG target	-	material flow simulation	Allwood et al. (2010)
MIL13	World	x					GHG target	-	material flow and technical energy simulation	Milford et al. (2013)
IEA17	World		x				GHG target	soft link to IEA energy supply model	TIMES-based linear optimisation	IEA (2017)
IEA09	World						GHG target	softlink to IEA world energy model	stock exchange model	IEA (2009)
RUJ16	World					x	GHG target	endogenous	econometric + multinomial logit	Van Ruijven et al. (2016)
BEL09	World		x				GHG target	soft link to POLES model	invest simulation	Bellona (2008)
SEI09	EU27	x					GHG target	one-way link to supply module	technical energy simulation	Heaps et al. (2009)
BCG13	EU27	x					potential	(energy prices given)	technical energy simulation	Boston Consulting Group/VDEh (2013)
JRC12	EU27		x				potential	(energy prices given)	invest simulation	Joint Research Centre (2012)
BEL08	EU27		x				GHG target	soft link to POLES model	invest simulation	Bellona (2008)
ARE16	Germany	x					potential	-	technical energy simulation	Arens et al. (2016)
WSP15	UK	x					potential	-	(scenario tool)	WSP/Parsons Brinckerhoff/DNV GL (2015)
ROO14	Northern Europe	x					potential	-	technical energy simulation	Rootzen et al. (2014)

For the purpose of clustering the approaches and to get an understanding of how the results shown below were developed, the studies have been further differentiated.

One dimension is the model type as described above in section 4.1. Regarding the steel sector there are studies using technical energy simulation models, invest simulation model and optimisation models. Only one study deploys total system optimisation, yet being explicit about the used technologies (technology enriched IMAGE model (RUJ16)). It can therefore be characterized as a hybrid model in regard to the top-down/bottom-up category. Other models like the IEA model (IEA17) only have a soft-link between different sub-models, allowing only for sector (i.e. industry sector) optimisation but not for system optimisation. Technical potential studies as well as target-orientated scenarios have been accounted for in the set of studies.

The studies examined also differ in regard to their framework assumptions. Typically, future steel demand (or production volume) is an exogenous value, e.g. derived by econometric methods without any feedback of modelled steel production costs to demand. In our analysis we differentiate in some cases between market growth and declining/stable scenarios – as the impacts on GHG and/or technology choice differ substantially. A market development with an annual change of below 0.6% are rated as stable/declining here. Very few studies regard steel demand as endogenous. Studies aiming at revealing technical potentials often assume stable production in order to isolate the GHG effect of technology switch.

The choice of which technologies to consider needs to be made by the person developing the scenarios. Even if the model takes the decision which technology to choose in a certain scenario, the framework of technology options is always a selection that is done by experts. Therefore, we make a distinction between scenarios that regard i) only *energy efficiency* (of common processes), i.e. best available techniques, ii) CCS, and iii) a fuel switch to less carbon-intensive reducing agents. The latter strategy includes both incremental options like co-use of plastics in blast furnace as well as more radical switches to other production technologies such as direct reduction with natural gas or even hydrogen as reducing agent. The following Table 4 shows a categorisation of the scenarios analysed.

Table 4 - Categorisation of the analysed steel sector scenarios.

study	scenario	region	scenario horizon	steel market development	strategies analysed						GHG mitigation	
						fuel switch						
					CCS	incremental	biomass	DRI NG	DRI H_2	electrolysis	% to base year	[% p.a.]
ALL10	1	World	2050	growth							50%	1.6%
	2	World	2050	growth							39%	1.1%
	3	World	2050	stable/decline							50%	1.6%
	4	World	2050	growth							50%	1.6%
MIL13	5	World	2050	stable/decline	x			x		x	18%	0.5%
	6	World	2050	stable/decline	x			x		x	72%	3.0%
IEA17	7	World	2060	growth	x			x			47%	1.4%
	8	World	2060	stable/decline	x			x			91%	5.1%
IEA09	9	World	2050	growth	x	x	x	x	x		48%	1.5%
	10	World	2050	growth	x	x	x	x	x		48%	1.5%
RUJ16	11	World	2050	growth	x			x			94%	6.9%
	12	World	2050	growth				x			83%	4.3%
	13	World	2050	growth	x			x			89%	5.3%
	14	World	2050	growth				x			81%	4.1%
	15	World	2050	growth	x			x			77%	3.6%
	16	World	2050	growth				x			69%	2.9%
BEL09	17	World	2050	growth	x		x	x		x	82%	4.2%
	18	EU-27	2050	stable/decline	x		x	x		x	N/A	N/A
	19	EU-27	2050	stable/decline	x		x	x		x	N/A	N/A
SEI09	20	EU-27	2050	growth			x	x			N/A	N/A
BCG13	21	EU-27	2050	growth				x			17%	0.5%
	22	EU-27	2050	growth	x			x			47%	1.6%
JRC12	23	EU-27	2030	growth	x						-33%	-1.4%
	24	EU-27	2030	growth	x						-41%	-1.6%
	25	EU-27	2030	growth	x						-43%	-1.7%
	26	EU-27	2030	growth	x						-36%	-1.5%
ARE16	27	Germany	2035	stable/decline				x			32%	1.9%
	28	Germany	2035	stable/decline							57%	4.1%
	29	Germany	2035	growth	x						18%	1.0%
WSP15	30	UK	2050	growth	x	x		x		x	60%	2.4%
	31	UK	2050	growth	x	x		x		x	46%	1.6%
ROO14	32	Northern Eur.	2050	stable/decline	x		x				24%	0.7%

Note 1: Studies included are: ALL10: Allwood et al. (2010), MIL13: Milford et al. (2013), IEA17: OECD/IEA (2017a), IEA09: OECD/IEA (2009), RUJ16: Van Ruijven et al. (2016), BEL09: Bellevrat and Menanteau (2009), SEI09: Heaps et al. (2009), BCG13: Boston Consulting Group/VDEh (2013), JRC12: Pardo et al. (2012), ARE16: Arens et al. (2016), WSP15: WSP Parsons Brunckerhoff / DNV GL (2015c), ROO14: Rootzén and Johnsson (2015).

Note 2: Negative GHG mitigation values (red coloured) indicate an increase in GHG emissions

Before interpreting technology options indicated in the table it has to be pointed out, that this table only shows what kind of technology the model or the modeller *can* choose in the respective scenario, but not if it actually chose it.

The table reveals that *CCS* is analysed as an option in almost all scenario studies, even in mid-term studies with 2030 as a scenario horizon. However, in some scenarios the adoption is explicitly excluded due to acceptance issues.

Biomass has been regarded as an option in the pre-2010 studies. In the more recent scenario literature, biomass scarcity is considered as a major challenge and biomass use is therefore often excluded. One exemption is the study by Rootzén and Johnsson (2015), which is focused on Northern Europe with its considerable local biomass potentials.

Direct reduction of iron (DRI) with natural gas is also included in most scenarios, with few exceptions. In the Pardo et al. (2012) the option was excluded deliberately, as stakeholders doubted if the existing blast furnace route stock could be replaced by DRI before 2030.

DRI with hydrogen is not regarded in most of the scenarios. It is difficult to determine a plausible electricity price for this option, as water electrolysis can be operated in a flexible way. No model analysed here provided an electricity system integration deep enough to analyse specific hydrogen costs in depth. Recent progress in model development will probably improve that and allow for deeper analysis on Power-to-X (PtX) in the future.

Iron electrolysis is the only real break-through technology, but very difficult to assess in economic models as the technology has been explored only on a laboratory scale. Some models, however, regard a partial phase-in.

4.3.2 Steel demand and production (incl. split primary/secondary)

One of the main drivers for the future energy demand and GHG emissions of the steel industry is the future level of steel production, which depends on the development of steel demand. The greater part of the decarbonisation scenarios analysed assume that steel demand and production will further increase in the future. Only 30% of the global scenarios and none of the EU scenarios assume that steel production will remain stable or decrease in the respective region. The following figure shows the assumed development of the sum of primary and secondary steel production clustered by target year (2030 and 2050), development of production (growing and stable/declining), regional delimitation (World and EU), and scenario study for 27 scenarios.

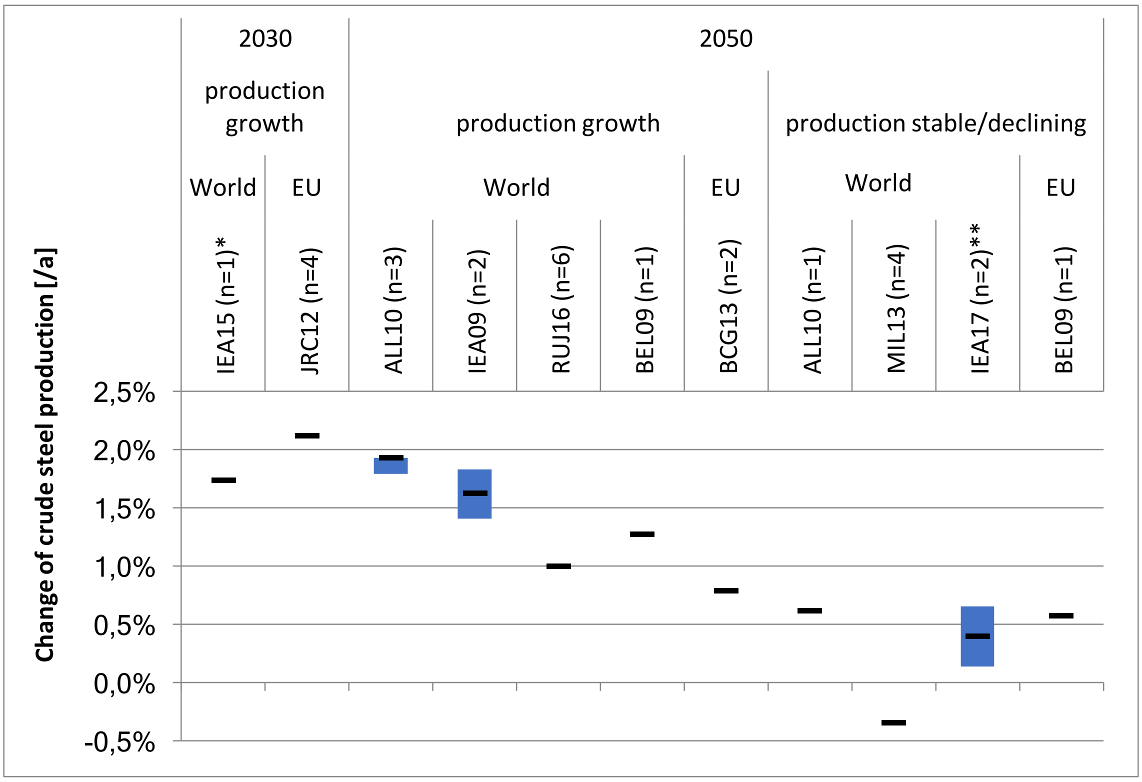

Figure 8 - Average annual change of crude steel production between base and target year

Note: * Target year 2025. ** Target year 2060.

Steel is predominantly produced via two main routes: the blast furnace-basic oxygen furnace (BF-BOF) route and the electric arc furnace (EAF) route. In the year 2014 the share of the secondary route reached a share of 39% in the EU28 (World Steel, 2016). The following table provides an overview of these two different steelmaking routes.

While iron ore is the basic raw material used in primary steel production, secondary steel production uses scrap steel (recycled steel). In scope of this analysis it is necessary to distinguish between primary and secondary steel production, because the specific energy demand and related GHG emissions of secondary steel production are each well below those of primary steel production (see Table 5). Energy and GHG balance of the primary and secondary route can be expressed in many different ways, depending on the system boundaries used (rating of electricity produced and consumed, rating of by-products), but the dimension of difference between the two routes remains approximately the same.

Table 5 - Specific final energy demand and CO_2 emissions of primary and secondary steel production in the EU27 in 2010

	Primary steel production	Secondary steel production
Specific final energy demand [GJ/t crude steel]	15.8	2.74
Specific GHG emissions [t CO_2/t crude steel]	1.82	0.25

Source: Pardo et al. (2012)

Scrap availability limits the amount of steel produced through the secondary production route. As the amount of scrap and the scrap recovery rates are expected to rise in the future, the share of scrap steel in the total volume produced is expected to rise from 30% globally in 2010 to 40% in the respective target year (2050), while for the EU27, the share is projected to increase from app. 40% to 50% in scenarios that assume an increase in the total amount of steel produced.

In the global scenario studies, where the steel production is assumed to remain stable or decline, a stronger increase of the share of scrap steel to nearly 60% by 2035 and almost 75% by 2050 is achieved (Figure 9).

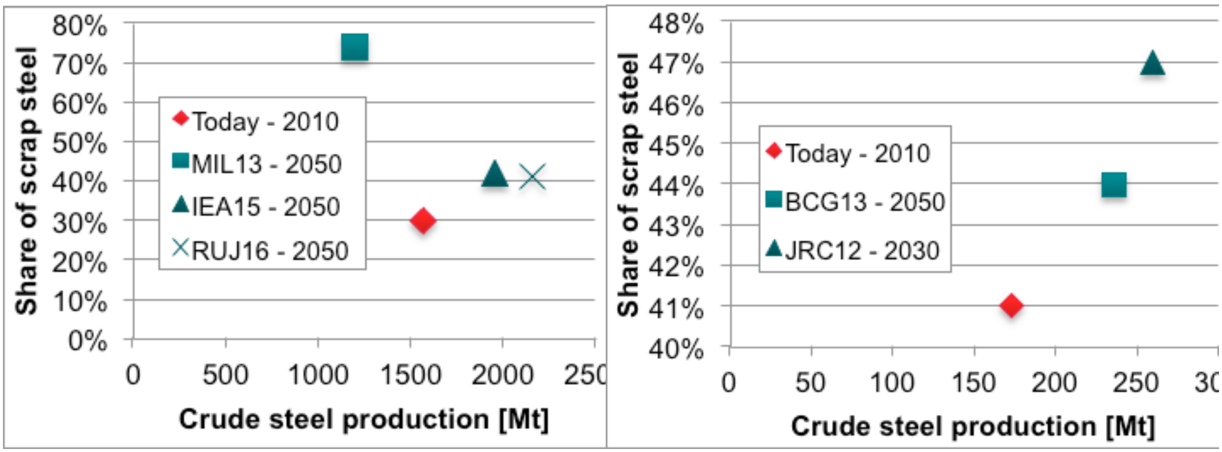

Figure 9 - Share of scrap steel in total crude steel production globally (left) and in the EU (right)

4.3.3 Final energy demand and GHG emissions

Final energy demand

The scenario studies' expectations of the future development of energy efficiency is indicated by the amount of final energy used to produce one ton of crude steel. Globally, the scenario studies show a decreasing specific final energy demand with a value of 10.9 to 13.4 GJ/t crude steel by 2050. This is equivalent to an average annual reduction of between 0.8% and 1.7% with a median of 1.4% (see following figure). Compared to the value of 21 GJ/t crude steel reported for 2014 (see above) this equals to a reduction by 36% to 48%.

A clear correlation of specific energy use and technology options available cannot be observed (see following figure). Differences there may be compensated by differences in the share of the scrap steel route.

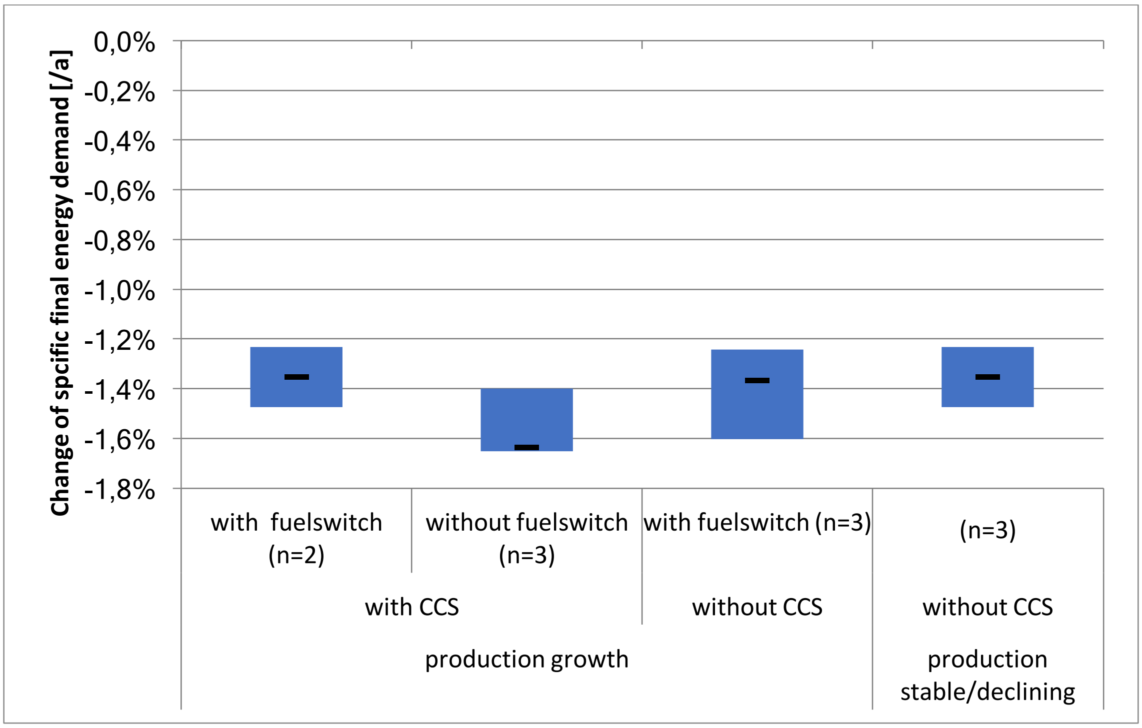

Figure 10 - Change in specific final energy demand globally until 2050

Total final energy demand differs between the scenarios (not indicated in a figure), but most of the effects can be attributed to the future steel production volume assumed in the scenarios.

GHG emissions

The global specific GHG emissions are well above the specific emissions in the EU. In 2010, the global specific GHG emissions were about 60% above the EU's specific emissions (ca. 2 compared to ca. 1.25 tCO_2/t crude steel produced) (Pardo et al., 2012; Van Ruijven et al., 2016). So a comparison of the global long-term scenario studies and a parallel EU comparison allows for a better comparison of the effects of the various mitigations options.

The development of the steel industry's overall GHG emissions is influenced by a number of factors including future steel production volumes and energy efficiency improvements (see above). The third factor is emission intensity, which is influenced by the choice of technology (incl. primary/secondary steel or CCS) and energy carrier. The following figure provides an overview of the scenario studies' average annual changes in the steel sector's GHG emissions until 2030 and 2050. It shows that in the short-term scenarios (with 2030 as target year), annual GHG emissions even slightly increase. It has to be pointed out here that the EU 2030 scenarios belong to only one study by Pardo et al. (2012), which takes a simulation approach, and does consider CO_2 constraints only indirectly (via CO_2 prices).

The long-term scenarios (with 2050 as target year), however, already project a reduction of GHG emissions by 2030.

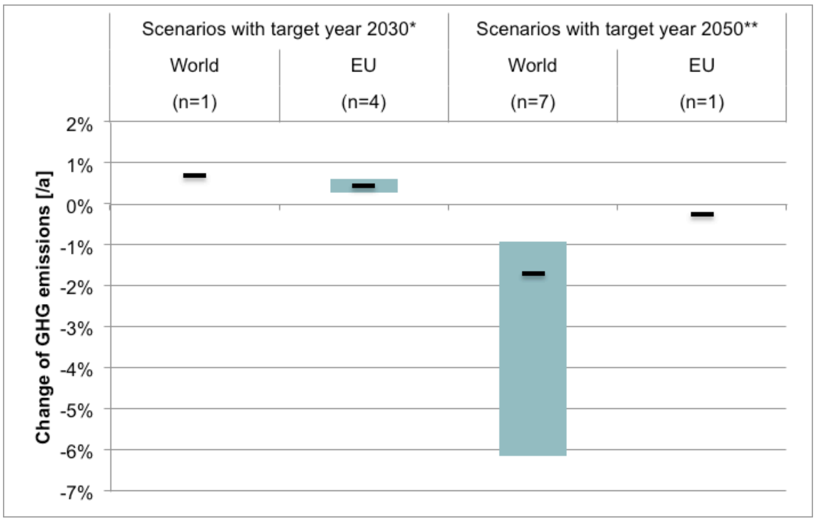

Figure 11 - Average annual changes of the steel sector's GHG emissions until 2030 and 2050

Note: * The world scenario has 2025 as target year. ** Two of the world scenarios have 2060 as target year.

When comparing the GHG emissions reductions, we again differentiate between technology options and production volume development.

Figure 12 shows that the scenarios achieving the greatest reduction in GHG emissions rely on CCS as a mitigation option. However, the differences between scenarios relying on CCS are large, ranging from an average reduction of only 1% per year to a reduction of 7% per year. Overall, this corresponds to a reduction from currently about 2,500 $MtCO_2$ to between 1,500 $MtCO_2$ (in scenario with lowest reduction in GHG emissions) and less than 500 $MtCO_2$ (in scenario with highest reduction in GHG emissions) for global steel production by 2050.

In the scenarios where CCS is not applied, the use of alternative energy carriers leads to an average annual reduction of GHG emissions of between 2.9% and 4.3%. The GHG reduction of the median scenario (4.1% p.a.) is close to the median scenario study of scenarios with CCS (3.6% p.a.).

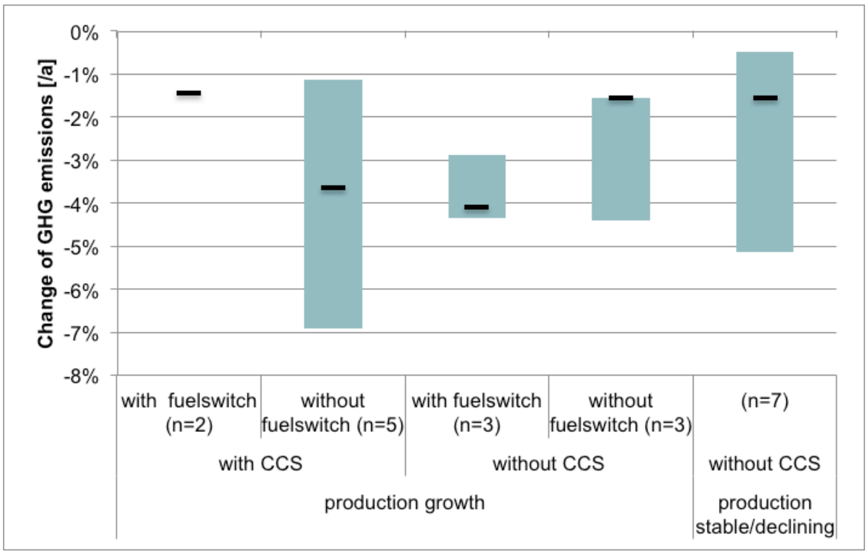

Figure 12 - Average annual change in GHG emissions of steel production in global scenarios with target year 2050

Across all global scenario studies, the deepest GHG emission reduction is achieved in an IEA scenario (IEA, 2017) with a reduction of 93% in 2050 compared to 2010 (equals 7% p.a.).

As said before emission intensity change can be addresses by fuel switch or CCS. The following figure finally displays the range of emission intensity values ranging from 100 kg CO_2 / GJ in 2030 (which is even slightly above steam coal) to 7 kg CO_2/ GJ in 2050. The latter value is reached by 100% application of CCS in primary crude steel production, as well as a decarbonisation of the electricity sector, indirectly decarbonising the EAF route.

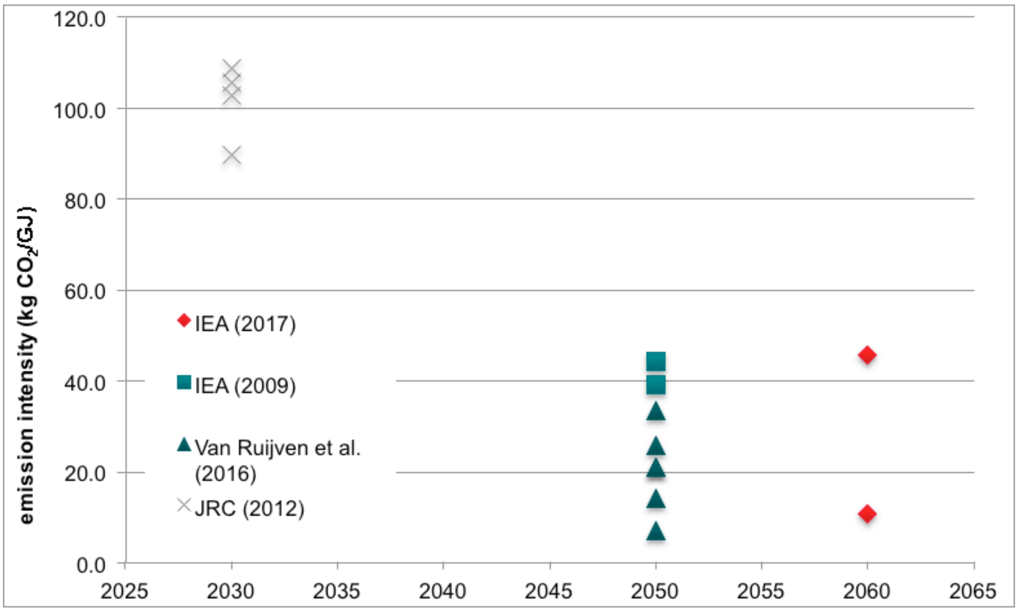

Figure 13 - emission intensity in steel sector scenarios. Source: Own calculations.

4.4 Plastics Industry

The plastics industry is part of the chemical industry, which is considered the most energy-intensive industry in Europe in 2015 – using about 20% of total industrial final energy consumption (OECD/IEA, 2017b). The chemical industry is involved in the production of (1) petrochemicals, (2) basic inorganic products (e.g. fertilizer, chlorine), (3) polymers (e.g. plastics, rubber and fiber), (4) specialty chemicals (dyes, paints) and (5) consumer chemicals (CEFIC, 2016).

Products derived from the steam cracking process (such as the „high value“ chemicals, HVC, also known as „basic“ chemicals) are the second most carbon-intensive in the European chemical sector (18% of total GHG emissions in chemical industry) [with nitric acid being first] (Ecofys/Fraunhofer-ISI/ Öko-Institut, 2009). Process energy in the chemical sector consists predominantly of electricity and natural gas (see Annex I). Electricity is mostly used for machine driving (55%) and electro-chemical processes (13%), whereas natural gas is mostly used for boiler use, combined heat and power production (CHP) and/or cogeneration (55%) and process heating (35%) (EIA, 2017).

The majority of high value chemicals [or 20% of total production and sales in the petrochemical and specialty chemical sector in Europe (CEFIC, 2016)] is used in the production of polymer and plastic production. There are five high-volume families of plastics. These are polyethylene (including low density (LDPE), linear low density (LLDPE) and high density (HDPE)), polypropylene (PP), polyvinylchloride (PVC), polystyrene (solid PS and expandable EPS) and polyethylene terephthalate (PET). Together the big 5 account for around 73% of all plastics demand in Europe (Plastics Europe, 2016).

4.4.1 Available models and scenarios (incl. clustering)

To draw out insights on possible decarbonisation strategies for the plastics industry, we have selected and analysed 13 futures studies from academic and non-academic sources (see Table 6). Overall, the majority of available studies focus on main chemical products (e.g. ammonia, methanol, olefins in general or specified to ethylene and/or propylene) due to the complexity of the chemical industry and the variety of products and production processes (IEA, 2009). Decarbonisation strategies for the chemical sector and its subsectors cover therefore a broad range in perspective, varying in terms of analytical, geographical and temporal scope and system focus.

- The studies show differences in analytical perspective, ranging from literature reviews (Åhman et al., 2012), to results of stakeholder surveys (Lewe et al., 2011), to modelling exercises [e.g. (CEFIC/Ecofys, 2013); Dornburg et al. (2008); IEA (2013)]. Each study may shift the focus of analysis to a different element – such as value added, production, energy demand, emissions, employment, sales etc. – for which different units may be used (Mt of product, or total sales).

- The scope of assessment varies per study – which may involve a broader system or a more narrowed down perspective, with a specific topic of interest. Semantics and definitions may also very, which leads to data comparability challenges. For example, the chemical industry may be referred to as the organic chemical market (Dornburg et al., 2008) or defined by a varying subset of basic chemicals (DECHEMA, 2017; IEA, 2013). Studies may also focus on the developments of a specific (bio-based) chemical (Dornburg et al., 2008; Wolf et al., 2005), which complicate a broader comparative analysis.

- Various studies on possible future developments have been scrutinised, including both business-as-usual (baseline) and decarbonisation scenarios. The baseline scenarios may include assumptions on climate policies or expected temperature increase (IEA, 2013) or assumptions on frozen or autonomously improving efficiencies (CEFIC/Ecofys, 2013). Decarbonisation scenarios may range from exploiting the maximum available and emerging technical potential of mitigation options (DECHEMA, 2017; IEA, 2013), to specific temperature or concentration targets in line with global international agreements (e.g. limiting global temperature change to 2°C) (Schade et al., 2009), or look into the effect of carbon taxation schemes on energy demand and emissions (Daioglou et al., 2014).

Due to the lack of a dominant focus in the selected literature, we focus on the chemicals associated with plastic production (such as ethylene and propylene, or olefins).

Table 6 - Overview of the selected studies on the decarbonisation of the chemical industry

Efficiency route:				**EMISSIONS**		**ENERGY**	**RESOURCE**		
Study	**geographical scope**	**Type of study**	**System boundary**	**CCS**	**Fuel and feedstock switching**	**Technological substitution / process innovation**	**Material efficiency**	**Industrial symbiosis**	**Energy recovery**
Lechtenböhmer et al. (2015)	Germany (State level)	Modelling study	Chemical sector (Ethylene)	X	x	x			
Åhman et al. (2012)	Sweden	Literature review	Industry wide (basic chemicals)	X	x	x			
Lewe et al. (2011)	EU	Survey	Chemical sector		x	x			
Fischedick et al. (2014)	Global	Literature review	Industry wide	x	x	x	x		
Dornburg et al. (2008)	EU25	Modelling study	Chemical sector		x				
Daioglou et al. (2014)	Global	Modelling study	Chemical sector	x	x	x	(x)		
Broeren et al. (2014)	Global	Modelling study	Chemical sector			x			
Allwood et al. (2010)	Global	Modelling study	Industry wide	x	x	x	x		
CEFIC (2016)	EU	Modelling study	Chemical sector	x	x	x			
IEA (2013)	Global	Modelling study	Chemical sector (18 basic chemicals)	x	x	x	x		x
WSP Parsons Brunckerhoff / DNV GL (2015a)	National	Modelling study	Chemical sector	x	x	x	x	x	x
Schade et al. (2009)	EU27	Modelling study	Chemical sector	x	x	x	x		x
DECHEMA (2017)	EU	Modelling study	Chemical sector		x	x	x	x	x

Several classes of decarbonisation strategies have been studied for the chemical sector in the available literature. The literature either individually or collectively assessed each of these classes in terms of their long-term mitigation potential. We can identify the following decarbonisation classes and strategies:

Emission efficiency

Emission efficiency strategies entail the shift from carbon-intensive fuels and feedstocks to less carbon intensive or carbon-neutral alternatives, or sinking excess carbon emissions via carbon capture and storage technologies. We distinguish between the following categories:

- **Carbon capture and storage (CCS):** CCS is considered a strategy for the chemical industry to reduce (direct) CO_2 emissions (Åhman et al., 2012; Fischedick et al., 2014; IEA, 2013; Schade et al., 2009; WSP Parsons Brunckerhoff / DNV GL, 2015a). However, we observe that broader integrated studies are more likely to assume CCS to be part of the industrial decarbonisation strategies than the more specific studies. A reason for this could be that the broader studies tend to formulate specific (and ambitious) GHG emission or temperature targets, while many of the more specific studies (especially those commissioned by industry stakeholders themselves) do not, making it more likely in the broader studies that CCS is required as a mitigation option.

- **Fuel and feedstock switching;** Process energy can be derived from low-carbon energy sources to power the production processes. Electrification, or power-based heat and steam generation, is considered an important route to decrease emissions. Similarly, the chemical sector can substitute petrochemical feedstock for alternatives, such as bio-based alternatives or other (platform) chemicals synthesized from hydrogen (e.g. methanol). Current bio-based routes to chemical feeds, however, require significant improvements to the overall energy consumption and costs to be widely used for large-scale chemical feedstocks (IEA, 2013). The production of hydrogen from low-carbon electricity is also considered an important route. Hydrogen can be used as a feedstock for the production of ethanol, olefins and aromatics (DECHEMA, 2017), enabling CO_2 recycling and avoiding the use of fossil feedstocks. Similar to bio-based materials, significant improvements to the energy efficiency and costs are needed to fully exploit the potential of this route as these are currently only interesting in terms of a GHG mitigation perspective (IEA, 2013).

Energy efficiency

Efficiency measures entail the optimisation of processes (realising the optimal balance in conversion efficiency) and production methods in the chemical industry:

- **Technological substitution / process innovation**: Steam cracking is the most energy-intensive process in the chemical industry. Upgrading all steam cracker plants to the best available technology could reduce energy demand by up to 30% (Fischedick et al., 2014) . To achieve a higher energy saving potential in the chemical industry, other processes would be needed in which steam cracking is avoided, e.g. via catalytic cracking of naphtha or methanol-to-olefin (MTO) processes (IEA, 2013). However, some alternative routes may increase the emissions efficiency at the expense of higher energy demand (e.g. bio-based chemicals and MTO).

Resource efficiency

Resource efficiency or the utilisation of waste-as-feedstock is also a form of efficiency being considered in the chemical industry. We distinguish between the following categories:

- **Material efficiency**: Recycling of polymers and the use of polymer waste as feedstock for chemical processes contains large prospective energy savings potential. Various routes are available to the chemical industry to recover material, e.g. via mechanical recycling (repurposing existing materials without modifying their chemical bonds) or chemical recycling (modifying the material's molecular bonds to recover hydrocarbons). Published estimates of the potential of material efficiency to contribute to GHG emission reductions vary, ranging from optimistic (DECHEMA, 2017) to more conservative (Daioglou et al., 2014), which can be attributed to varying assumptions on the energy demand, carbon footprint, costs, properties, etc. of the recycling systems.

- **Industrial symbiosis:** Waste streams (e.g. excess heat) in other industries could provide the essential building blocks for the chemical industry. Particularly the collaboration with the steel industry is considered promising, as the off-gases of steel manufacturing can be repurposed in the chemical industry (DECHEMA, 2017). WSP Parsons Brunckerhoff / DNV GL (2015a) consider this only feasible when clustering of industries can be realised.

- **Energy recovery**: Energy recovery refers to the combustion of waste plastics with energy recovery and the (re)use of the associated CO_2 emissions in the chemical production processes (recirculation of molecules) (DECHEMA, 2017).

4.4.2 Plastics demand and production (incl. recycling issues)

The energy consumption and GHG emissions of the chemical sector scale with the production volume of chemical products. Projections on how production volumes for basic chemicals may evolve over time are limitedly available and subject to uncertainty as most adopt exogenous and continuous growth assumptions. For simplicity, we only plot the development of light olefins or HVC in this section as these represent the main intermediates to plastic production, and leave the replacement rate or production volumes of equivalent chemicals out of this scope (such as methanol or bio-based alternatives).

The IEA (2013) presents a global estimate, suggesting that global demand for (petro)chemical products will triple by 2050 if no further environmental policy is enacted (see Figure 14), with the largest growth in China and Latin America. Relatively slower growth (1.35% per annum) is expected for Europe. Under decarbonisation policies, the IEA (2013) adopts explicit assumptions on decoupling demand from economic growth. These assumptions consider a decline in the annual average growth rate due to increased recycling of post-consumer plastic wastes which reduce the need for HVCs.

DECHEMA (2017) adopts more-or-less a comparable growth rate for business-as-usual production volumes, assuming a continuous supply of products and materials by the European chemical industry with a 1% growth per annum. Under decarbonisation assumptions (maximum technical potential scenario) DECHEMA depicts a massive expansion in the production of low-carbon methanol as the scenario foresees this as the main source for olefin production.

Other studies also adopt similar rates of change for the chemical industry. Dornburg et al. (2008) adopt a very similar growth rate for their middle-of-the-road scenario (1.5% p.a.) for the European organic chemical market as a whole. High and low assumptions on growth are set at 0% to 3% per year, based on expert consultations. WSP Parsons Brunckerhoff / DNV GL (2015a) assume a bandwidth ranging from a -0.5% p.a. decline (challenging world), to a 2% p.a. growth (collaborative growth), with a 1% p.a. growth in a "current trends" analysis.

In Lechtenböhmer et al. (2015), depicting a local demand projection, a decline of ethylene production is expected as a result of lowered gasoline and diesel production in the local refineries, following lower fuel demand in transport.

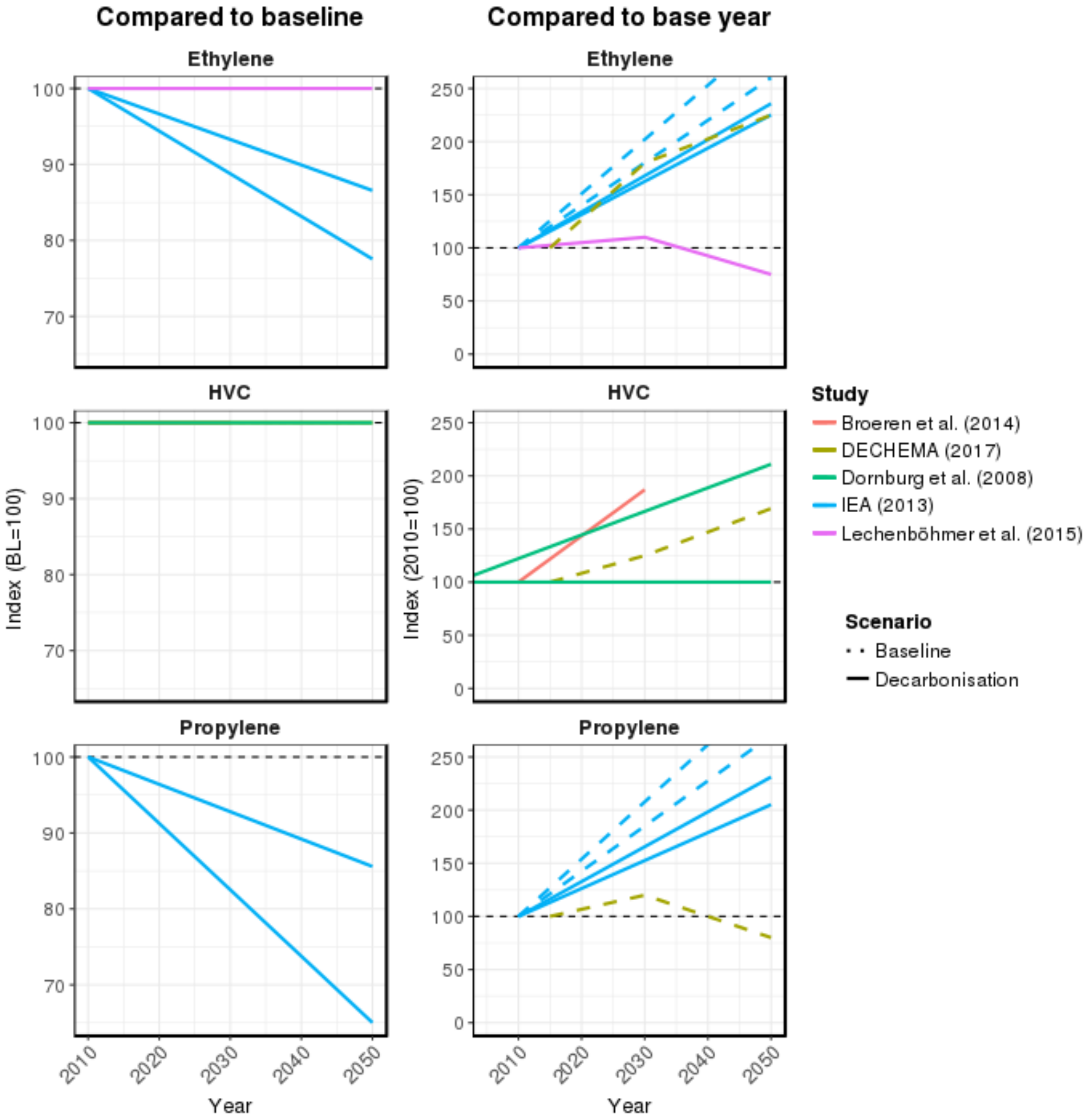

Figure 14 - Overview of production volume changes in the chemical sector over time.

Note: IEA (2013) covers global production. Lechtenböhmer et al. (2015) covers regional production expectations. All other studies represent chemical growth in the EU. For Dornburg et al. (2008) we plotted the "organic chemical market" growth assumptions to HVC production.

4.4.3 Total final energy consumption and GHG mitigation

4.4.3.1 Change in total final energy consumption

Several studies have assessed the potential energy demand reduction of the chemical industry as a whole (CEFIC/Ecofys, 2013; Lechtenböhmer et al., 2015; Schade et al., 2009). When no autonomous energy efficiency improvements are considered (e.g. frozen efficiencies to the studies' respective base years) this leads to an overall increasing demand under business-as-usual considerations (CEFIC/Ecofys, 2013). However, when autonomous optimisation efforts and investments are included this may lead to a decline in total energy demand (Schade et al., 2009). With strict enforcement of decarbonisation policies, greater energy demand reduction efforts are considered to potentially lead to a decline up to 45% by 2050 (CEFIC/Ecofys, 2013).

Alternatively, IEA (2013) has specifically addressed the potential development trajectory for olefin production. By considering best practice technologies (BPT) and emerging technologies, in this case catalytic cracking of naphtha, a 25% to 50% energy demand reduction can be achieved by 2050 relative to 2005 (assuming an overall static growth in olefin production for EU). Smoothening the implementation of available BPT, either through the replacement and refurbishment of existing plants and the construction of new plants at BPT efficiency level, is therefore an important (single) measure for saving energy in the chemical sector in the coming decades (IEA, 2013).

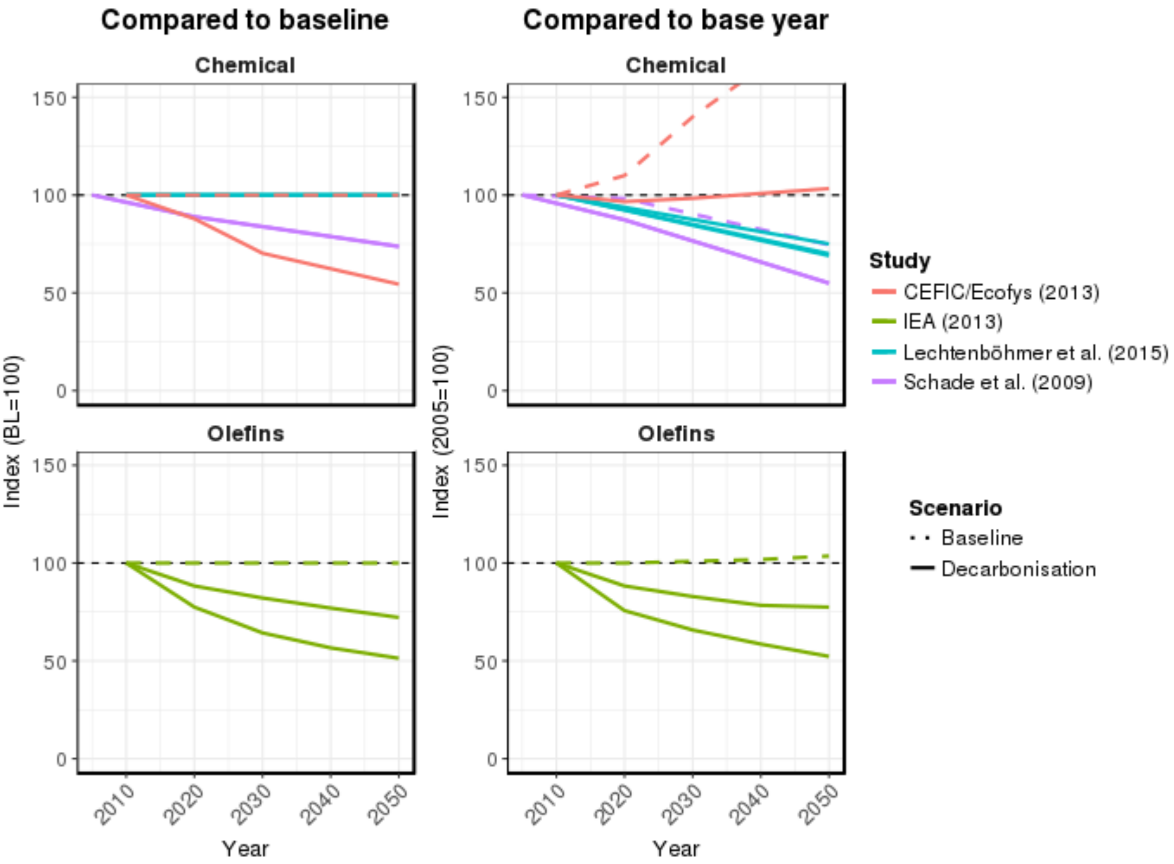

Figure 15 - Change in final energy consumption for the chemical industry in EU27.

Note: Lechtenböhmer et al. (2015) depict reductions on federal state level.

4.4.3.2 Direct and indirect (CO_2) emission reductions

Without any efforts to decarbonise the chemical industry, studies project that the sector's total CO_2 emissions will increase (see Figure 16). In WSP Parsons Brunckerhoff / DNV GL (2015a), the baseline scenario initially assumes a decline in emissions as electricity from the power grid is assumed to become less carbon intensive over time. However, this effect is eventually countered by production growth after 2020 in the chemical sector (WSP Parsons Brunckerhoff / DNV GL, 2015a).

Both CEFIC/Ecofys (2013); WSP Parsons Brunckerhoff / DNV GL (2015a) project declining emissions under deep decarbonisation efforts or maximum technical implementation scenarios – leading up to near carbon neutrality in the chemical sector by 2050. The DECHEMA (2017) study describes a more radical emission reduction potential, showing negative emissions by 2035 under maximal technical implementation. This implies that CO_2 emission reductions can potentially be greater than the associated emissions of the industry, as a result of the considered negative carbon footprint of alternative feedstocks (primarily methanol and bio-feedstock).

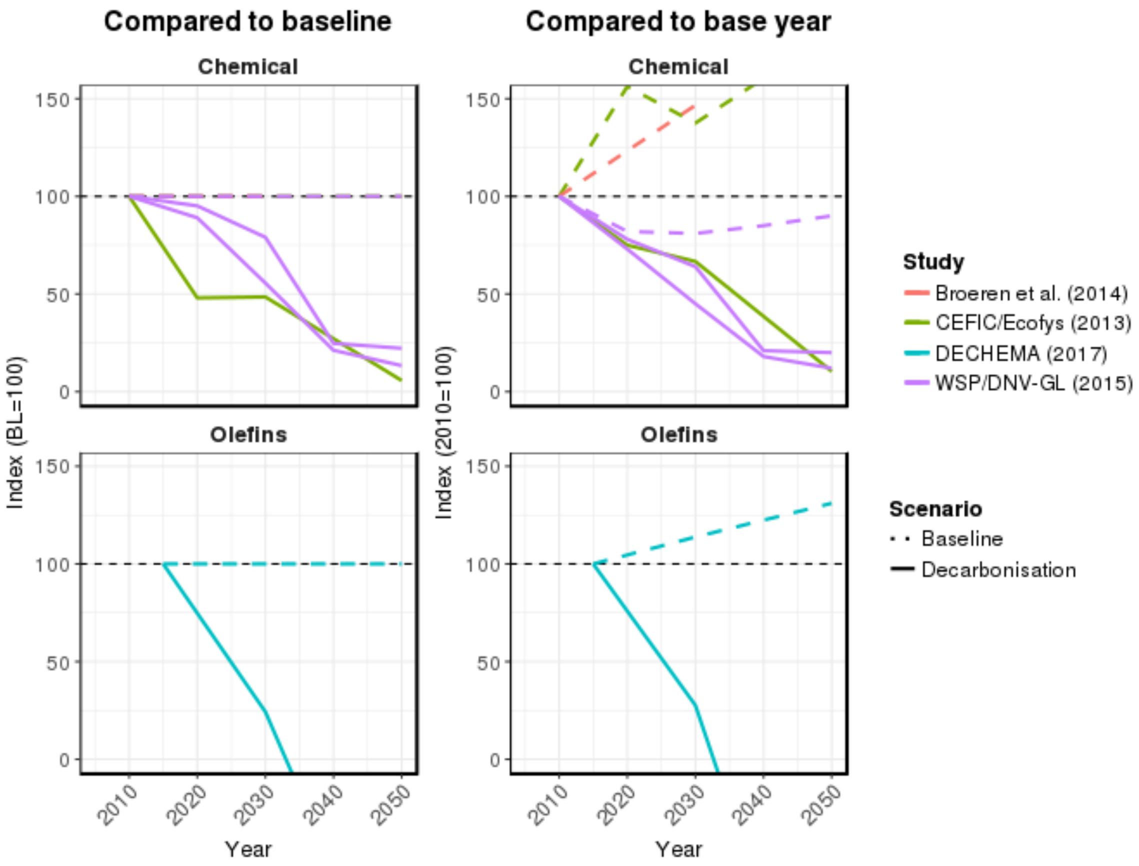

Figure 16 - Overview of considered emission pathways for the European chemical industry in literature.

4.5 Paper industry

The paper industry consists of two major steps: The production of the raw material (the fibres) at the first step and the actual paper and paper board making with a paper machine.

At the first step there are three major routes:

- the production of chemical pulp from wood
- the production of wood pulp from wood and
- the recycling of waste paper.

To acquire some of the standard paper qualities a certain amount of chemical pulp is needed at the second step. Chemical pulp production delivers a significant amount of biogenic by-products, in particular black liquor. In an integrated mill the energy content of the by-products typically exceeds the energy need at the downstream paper making process.

The second step of paper making is energy intensive, as there is a need of steam and electricity. So combined heat and power (CHP) is an attractive technology in this sector, already used today in paper mills. The studies and scenarios covering the paper industry are listed in Table 7.

Table 7 list of scenario studies on the paper (and pulp) sector

Study	Geographical scope	Scenario	Energy efficiency	Fuel switching	electrification (Power-to-Heat)	CCS	Source
Explicit focus on paper sector							
FLE12	Germany	FLE12-TEC	x				Fleiter et. al (2012)
WSP15	UK	WSP15-40	x	x			WSP et al. (2015d)
		WSP15-MT1	x	x			
		WSP15-MT2	x	x			
CEP11	global	CEP11-Roa	x	x			CEPI (2011)
Paper sector part of analysis							
SEI09	EU	SEI09-MIT	x	x			Heaps et al. (2009)
IEA16	global	IEA16-2°C	x	x		x	OECD/IEA (2016)
IEA17	global	IEA17-2°C	x	x	x	x	OECD/IEA (2017)
		IEA17-<2°C	x	x	x	x	
IEA09	global	IEA09-LOW	x	x		x	OECD/IEA (2009)
		IEA09-HIGH	x				
LEC115	Germany (region)	LEC15-BAT	x	x			Lechtenböhmer et al. (2015)
	Germany (region)	LEC15-LC	x	x	x		
	Germany (region)	LEC15-CCS	x	x	x		

The system foci of the studies differ depending on the geographical scope. Countries like Germany and the UK have very view pulp production. So paper mills there depend on pulp imports and recycled paper and do not have the option of integrated production.

4.5.1 Paper demand and production (incl. recycling issues)

According to the OECD/IEA (2017), the global production volume of paper and board was about 400 Mt in 2014. All analysed scenario studies that provide data on paper and paperboard production project an increase in global production to about 500 to 700 Mt in 2050. However, more recent scenarios designed by the IEA project a slower increase of production levels (IEA17).

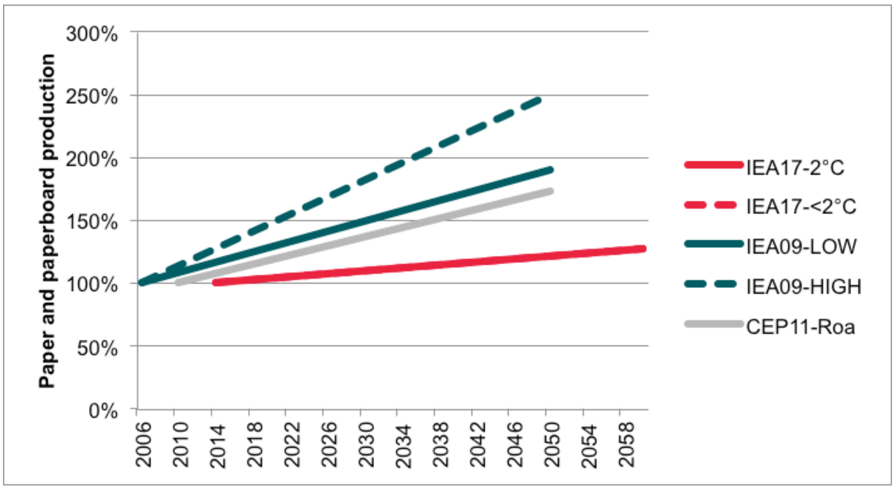

Figure 17 - Change in paper and paperboard production in relation to each scenario studies' base year (CEPI, 2011; OECD/IEA, 2009, 2017a).

4.5.2 Technologies regarded in the models and used in the scenarios

An overview on the general mitigation technologies taken into account by the respective scenarios is provided in Table 7 (above). A study with an explicit focus on energy efficiency in the German pulp and paper industry Fleiter et al. (2012) lists a number of energy efficiency measures for different production processes:

- **Mechanical pulp:** Heat recovery (TMP, GW), high-efficiency GW, enzymatic pre-treatment, efficient refiner and pre-treatment
- **Recovered fibers:** high consistency pulping, efficient screening, heat recovery from bleaching, de-inking flotation optimization, efficient dispersers
- **Paper:** efficient refiners, optimization of refining, chemical modification of fibers, steam box, shoe press, new drying techniques, heat recovery

IEA's long-term energy technology perspectives study (OECD/IEA, 2017) additionally lists CCS as an option. If biogenic (by-) products are used for the firing of cogeneration units with a carbon capture unit this option allows for net negative emissions (BECCS). An alternative way is the storage within a chemical product: black liquor as one major by-product of pulp production can be gasified; the syngas produced can be used in chemicals production.

Electrification of steam supply (Power-to-heat) is a further decarbonisation option, which has gained some importance in recent scenario discussion. Lechtenböhmer et al. (2015) and OECD/IEA (2017) explicitly model this option, which provides the opportunity to use renewable electricity in times with negative residual load and simultaneously to shut down CHP plants in these times.

4.5.3 Final energy demand and GHG emissions

In 2014, the global paper industry's final energy demand was about 6.000 PJ (OECD/IEA 2017). The scenarios show widely diverging trends in future global energy demand, from an increase by 80% to a decline by 10% by 2050. On the EU level, only one scenario study provides data on the future development of the paper industry's final energy demand. This scenario shows a decrease of final energy demand from 1.100 PJ in 2010 to 500 PJ in 2050 (Heaps et al., 2009).

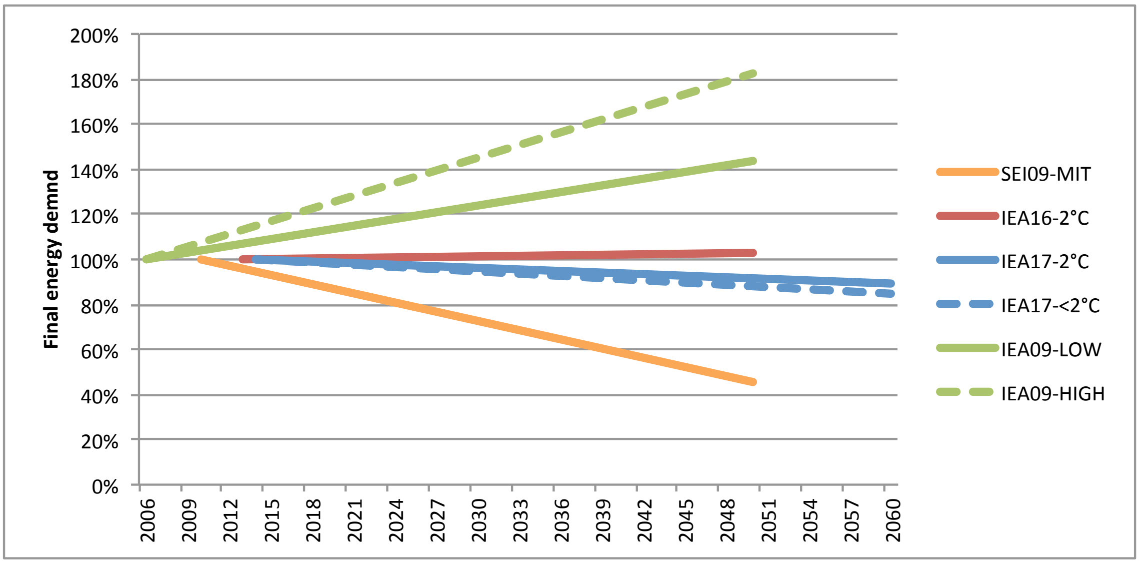

Figure 18 - Change in final energy demand for the paper industry in relation to each scenario studies' base year.

The direct GHG emissions account for about half of the paper industries' total GHG emissions and were about 200 $MtCO_2$ in 2014 globally (OECD/IEA 2017). The analysed mitigation scenario studies project a decrease in global GHG emissions of more than 80% by 2050 (see Figure 19). The scenario study that covers the UK even shows the potential for an almost complete decarbonisation of its paper industry (WSP Parsons Brunckerhoff / DNV GL, 2015d). While WSP Parsons Brunckerhoff / DNV GL (2015d) reach the same level via a complete fuel switch to biomass, OECD/IEA's (2017) most ambitious "beyond 2 degrees scenario" even makes use of BECCS at sites with chemical pulp production and of electric steam supply (power to heat), compensating for some fossil fuel use at other paper mills without chemical pulp production.

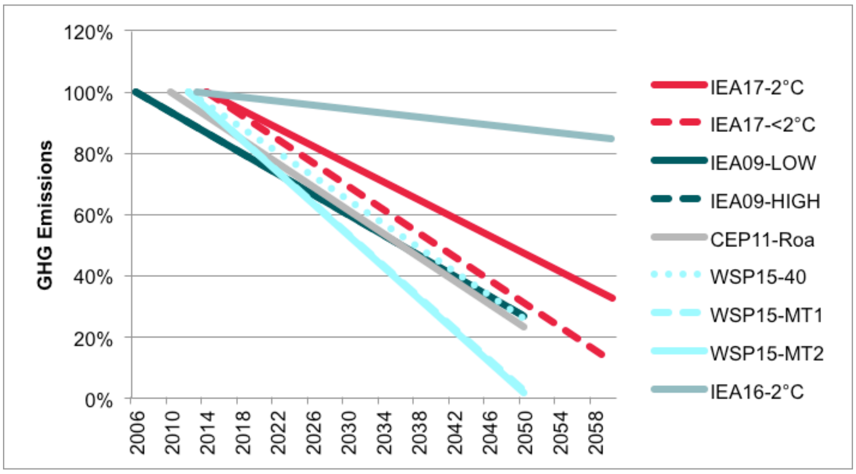

Figure 19 - Change in GHG emissions for the paper industry in relation to each scenario studies' base year.

Note: In IEA16 and IEA17 only direct emissions are considered.

In the same time horizon, the direct GHG emission intensity could decrease from around 30 tCO_2/TJ today to around 10 $tC0_2$/TJ in 2050, according to several decarbonisation scenarios of the OECD/IEA (see Figure 20). The most radical scenario of WSP Parsons Brunckerhoff / DNV GL (2015d) could not be assessed here due to missing quantitative information on energy use.

Figure 20 - Direct GHG emission intensity of final energy demand in the paper sector

Note: Only direct GHG emissions considered

4.6 Meat and dairy sector

The meat and dairy sectors are associated with the broader food, drink and tobacco industrial sector [ISIC 10-12, NAICS 311]. In total, the food sector has been the fourth most energy-intensive sector in Europe in 2015 (11% in total final energy consumption in industry) (OECD/IEA, 2017b). The food and drink sector is very heterogeneous, including subindustries like the dairy, fruit and vegetable preserving, meat processing, sugar and grain and oilseed milling sector (EIA, 2017 ; WSP Parsons Brunckerhoff / DNV GL, 2015a). Although generic processing techniques can be identified in the food sector (such as preparation, evaporation, rendering, mixing, conveying, etc.), each subsector contains specific processing technologies.

Improving the environmental performance of the food sector is associated with lowering the impact throughout various steps in the supply chain, from electricity supply, agricultural production, processing, transport, end-use and recovery. The overall energy consumption consists of electricity and natural gas for thermal energy (see Annex I). Electric energy is predominantly used for machine driving (43%) and process cooling and refrigeration (27%), whereas natural gas is used as input for conventional boiler use (58%) and process heating (29%) (EIA, 2017).

4.6.1 Decarbonisation studies on the food system

Studies focussing on food sector decarbonisation strategies are diverse – with a large body of literature focussing on the contribution and impact of agriculture (production) and to a lesser extent on the food processing and consumption sector. Aside from the heterogeneity in the scopes, there is also a wide variety in the type of indicator that is being reported (e.g. CO_2 intensity per unit product, unit calorie, etc., as described in Garnet et al., 2011).

We have selected three available studies that cover the food sector as a whole (see table 8).

Table 8- Overview of studies focussing on food sector decarbonisation strategies

Source	Reference scenario	Decarbonisation scenario	lifecycle	Geographical scope	Outlook	CCS*	Renewable energy technologies	Process optimisation / technological substitution	Energy recovery/ material efficiency	Behavioural change
WSP Parsons Brunckerhoff / DNV GL (2015a)	Business-as-usual	Max Tech	Food processing	UK	2050	x	x	x		
Audsley et al. (2009)	-	70% GHG emission reductions in the food system	Food production, processing and end-use	UK	2050		x	x	x	x
Schade et al. (2009)	Temperature increase of 4°C by 2100	2°C („450 ppm“) <2°C („400 ppm“)	Food processing	EU	2050	x	x	x		

*CCS in this instance implies the use of CCS in the power supply sector – leading to indirect emission reductions for the food sector

Two main routes are considered available for long-term decarbonisation in the food sector, namely carbon abatement and energy savings, for which the following measures can be identified:

Electrification of heat and process energy

Decarbonising power supply can be an effective measure to lower the environmental impact of the food sector. Via low-carbon electricity the total impact can be reduced. Renewable energy technologies, such as solar energy, can be utilised to provide a constant flow of moderate heat (Monforti-Ferrario et al., 2015). The use of biomass and bioenergy have also been addressed in WSP Parsons Brunckerhoff / DNV GL (2015b) as a potential renewable fuel type, which can be used in biomass boilers and CHPs. Alternatively, electrification can lead to additional gains through simultaneous grid decarbonisation efforts (e.g. by CCS in power).

Process optimisation / Technological substitution

The industry's energy demand is dependent on the need for industrial processing of food products, which varies per product. Decreasing the energy demand in the food sector is associated with improving the energy consumption per unit of production value. A lower energy demand per tonnage of product can be achieved via either more efficient production processes (e.g. in steam systems, process cooling and refrigeration, particular important for large manufacturers), more efficient support processes (e.g. lighting, ventilation, space heating, which are particularly important for small-to-medium enterprises), or efficiency in food transport (for which energy is used for both displacement and cooling). However, given the structural features of the sector, consisting of heterogeneous sets of enterprises, energy efficiency improvements are difficult to extend beyond the single plant test case (Monforti-Ferrario et al., 2015). Nonetheless, modelling studies make assumptions about the scalability of such process optimisation measures (Audsley et al., 2009; WSP Parsons Brunckerhoff / DNV GL, 2015b).

Material efficiency /Energy recovery

Upgrading residual streams– such as repurposing food waste to energy input or feedstock for biogas production - is a potential major source of renewable energy use in the food sector (Monforti-Ferrario et al., 2015). Another considered area of improvement is more efficient use of packaging materials (Danone, 2013) or food innovations that extend the shelf life of the products.

Behavioural change

Consumers can also be enablers of substantial energy and emission reductions in the food sector. Particularly dietary change, e.g. by reducing the meat consumption or substituting products for plant-based alternatives (see e.g. Stehfest et al. (2009); Tilman and Clark (2014)), is considered to be very effective in reducing the environmental impact of the food (and agricultural) systems (Monforti-Ferrario et al., 2015).

4.6.2 Meat and dairy demand and production

Food production volumes change over time, and are subject to confidentiality (e.g. due to small numbers of dairy enterprises it presents a risk for revealing identity) and uncertainty (e.g. due to changing preferences, or many small manufacturers) and varies per commodity. The OECD/FAO (2017) expects an overall growth in dairy product production in EU28, particular for skim milk powder (~2% p.a.). For the meat industry, an overall flat growth is expected for most meat products (all showing a <1% average annual, but declining, growth rate) (see Figure 21).

Growth rates of a similar extent are utilised in WSP Parsons Brunckerhoff / DNV GL (2015b) – adopting a continuous and sector-wide (exogenous) growth assumption, ranging of about 0% (pessimistic assumptions under the “Challenged world” scenario) to 2% (optimistic assumptions under the “collaborative approach” scenario).

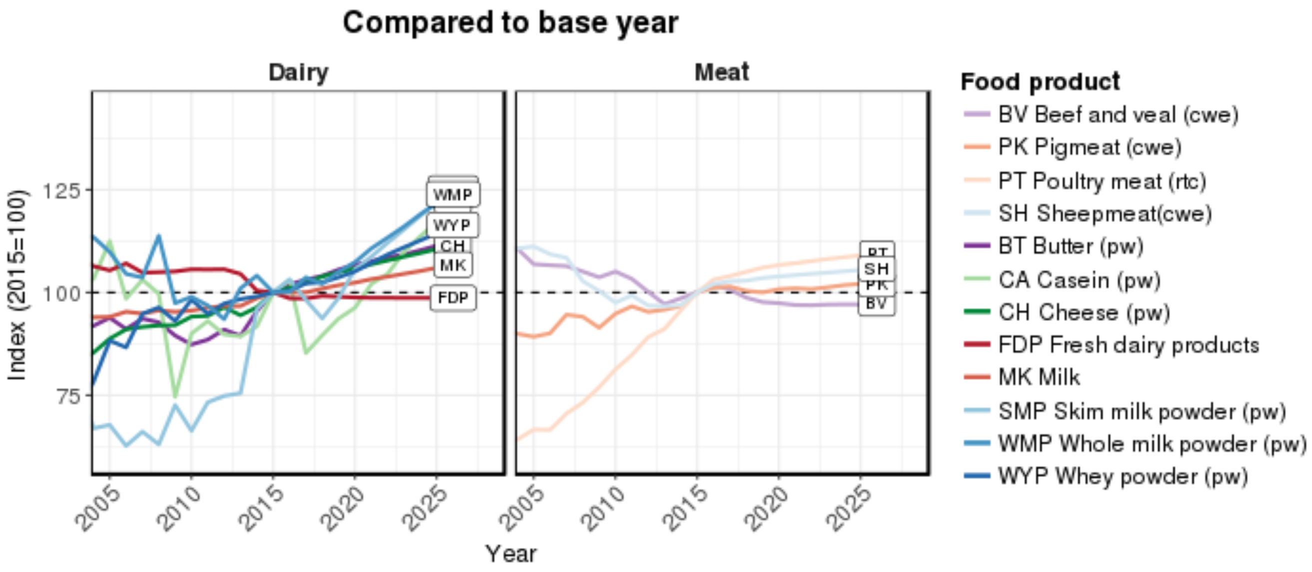

Figure 21 - Expected growth in production for EU-28, indexed to 2015 values Data adapted from OECD/FAO (2017)

4.6.3 Final energy consumption and GHG mitigation

4.6.3.1 Change in total final energy consumption

Only one single study has reported on the total energy demand and potential reductions in the food sector (Schade et al., 2009). The projected energy demand reduction are assumed to be a result of more general efficiency improvements in machine driving capital and cooling, leading to about 60% reductions compared to 2010 levels.

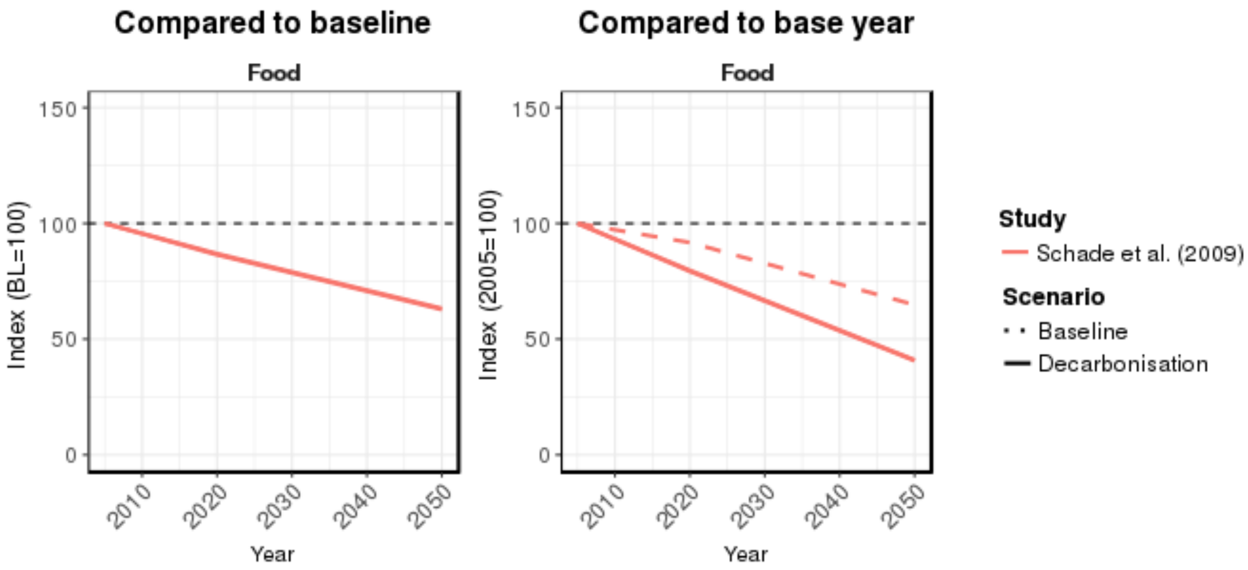

Figure 22 - Change in final energy consumption for the food industry in EU27.

4.6.3.2 Change in total direct and indirect (CO_2) emissions

The pathways considered in WSP Parsons Brunckerhoff / DNV GL (2015b) show emission reductions in the range of 60%-75% compared to 2012 levels for the food sector. The main gains are achieved via process design, biomass and bio-energy and the electrification of heat. Particularly in the latter case, this implies that the industry relies on the decarbonisation of the grid, e.g. via carbon capture and storage technologies or other means.

The study by Audsley et al. (2009) incorporates a broader set of measures that are applied over the full food supply chain (ranging from agricultural production, to processing, end-use and disposal or recovery, while embedding emissions from imports). All scenarios are aimed at meeting the 70% reduction target in 2050, for which varying assumptions are adopted for energy, consumption and technical measures to reduce emissions. The presented scenario in Figure 23 utilises the maximal implementation of all considered options, although scenarios devising more probable assumptions are expected to lead to 55% to 59% reductions by 2050 compared to the base year.

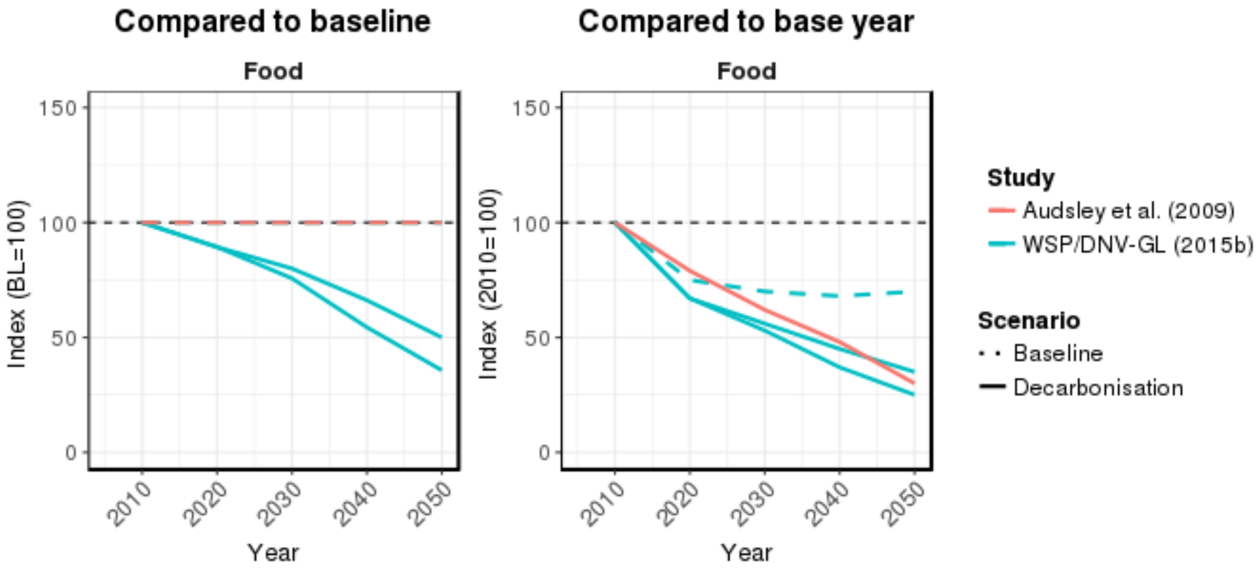

Figure 23 - Overview of the different decarbonisation and energy efficiency pathways (Figure taken from WSP Parsons Brunckerhoff / DNV GL (2015a))

5 Conclusions

In this deliverable we have assessed the available literature on long-term strategies to decarbonise five industrial sectors, specifically steel, plastics, paper and meat, and dairy. Via a structured literature review, we have performed a meta-analysis on the applied tools, methods and transition perspectives to draw out insights on the considered mitigation efforts per sector. We have specifically looked at perspectives focused at decarbonisation strategies in line with international climate objectives or those aiming at transforming current industries to low-to-no carbon alternatives over a medium-long timeframe (2050). Systemic changes have been measured by sampling the performance of three commonly reported indicators, respectively production volume, energy consumption and carbon emissions (for the industry as a whole or per unit of product). The quantitative analyses have been supplemented with qualitative information on the assumed long-term mitigation options per sector.

5.1 Reflections on the meta-analysis

Our stocktake of long-term decarbonisation strategies showed that the number of detailed studies on decarbonising specific industrial sectors is rather limited – with the exception of the steel sector. Furthermore, the studies varied in terms of scope (e.g. showing differences in geographical, sectoral, technological and temporal resolution), analytical focus (e.g. a broad range of modelling techniques are represented) and the level of detail being provided (with varying semantics and definitions). This leads to (data) comparability challenges across the selected literatures. Nonetheless, the following more generalizable conclusions can be made:

The available literature on low-carbon strategies for industry depict substantial potential for reducing energy demand and abating CO_2 emissions in all sectors

The literature on low-carbon strategies for industry shows that total final energy demand could potentially be halved by 2050, which appears to be independent of the sector considered. Simultaneously, specific strategies in the chemical and paper industries show potential to fully decarbonise the associated sector or process. Studies on the chemical sector make explicit assumptions on this being co-dependent on both the decarbonisation of the power supply sector and efforts by the chemical sector itself to implement radically new chemical production processes (e.g. methanol-to-olefin). The reliance on decarbonisation of power supply is also evident for the paper sector: the (relatively few) scenarios on this sector show a significant variety of possible futures, including deep decarbonisation and even net negative emissions at the global level. Net negative emissions rely specifically on bio-energy with carbon capture and storage (BECCS) in power supply. The BECCS strategy, however, is to be discussed in the wider context of electricity sector decarbonisation and the respective CCS infrastructure to be built.

Limited insights into cross-sector interdependencies are provided in energy system models

This holds not only for the integration of energy supply and industry (sector coupling) but also for intra-industry relations. In other words, the impact of decarbonisation of processes on the demand for products (including substitution) is generally not explicitly assessed by energy system models. From a modelling perspective, this can be explained by the difficulty of taking into account cross-price elasticities of inhomogeneous products. However, this omission narrows the picture of possible futures.

Relatively homogenous industries (such as steel and paper) allow a detailed quantitative assessment of long-term decarbonisation strategies

The analysed scenarios show a set of possible futures, including not only technological measures in the steel production process, but also closing of product cycles and material efficiency measures. The models that rely on an investment simulation approach, however, have not been used in a context of long-term deep decarbonisation. This implies that there seems to be a lack of an integrated forecasting/backcasting analysis with regard to deep decarbonisation at the European level.

For heterogeneous industries such as plastics and meat and dairy, the focus is mainly on decarbonising upstream processes

Relatively few comprehensive assessments of long-term decarbonisation strategies are available for industries with a wide range in value chains. Scenarios on the plastics sector focus on potential long-term developments for (upstream) intermediate products and processes (such as steam cracking products and processes, which rely on oil refinery products as a feedstock). Similar observations hold for the food sector, for which long-term decarbonisation is primarily associated with greening the agricultural sector.

A systematic and integrated assessment of alternative feedstock sources combined with a market analysis for transport fuels is generally still lacking, as well as an assessment of circular economy strategies. Yet, there are first generic studies assessing the potential of the plastics sector as a carbon sink to achieve net negative emissions.

5.2 Further considerations

The results of this report will be used as context for our own forthcoming modelling work during the REINVENT project, and will also be used as input for the planned stakeholder workshops. An important consideration in this regard is that most of the analysed scenario studies did not aim or realised full decarbonisation of the sectors, due to the respective scenario approach taken. In REINVENT, however, the focus is on fully decarbonising the industry sectors around mid-century – as this seems to align with the global objective to limit global temperature increase to well below 2°C, especially if a strong reliance on net negative CO_2 emissions is to be avoided (REF). Therefore, a remaining challenge is to combine backcasting with forecasting and simulation.

Furthermore, the observed lack of modelling tools for value chain integrated analysis also sharpened the view on the respective roles of the two REINVENT models, PBL's IMAGE model and Wuppertal Institute's WISEE, to overcome some of the shortcomings we observed. On the one hand, the optimisation model IMAGE can provide the needed energy system integration to analyse options of CCS and electrification in the whole energy system and ensure GHG accounting and target achievement (carbon neutrality) at the system level. On the other hand, the simulation model WISEE can regard the regional renewable potentials of existing industry clusters with cross-industrial product flows and existing infrastructures to enrich analysis and account for intra-EU regional differences.

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Annex I: Overview historical energy use per sector and carrier

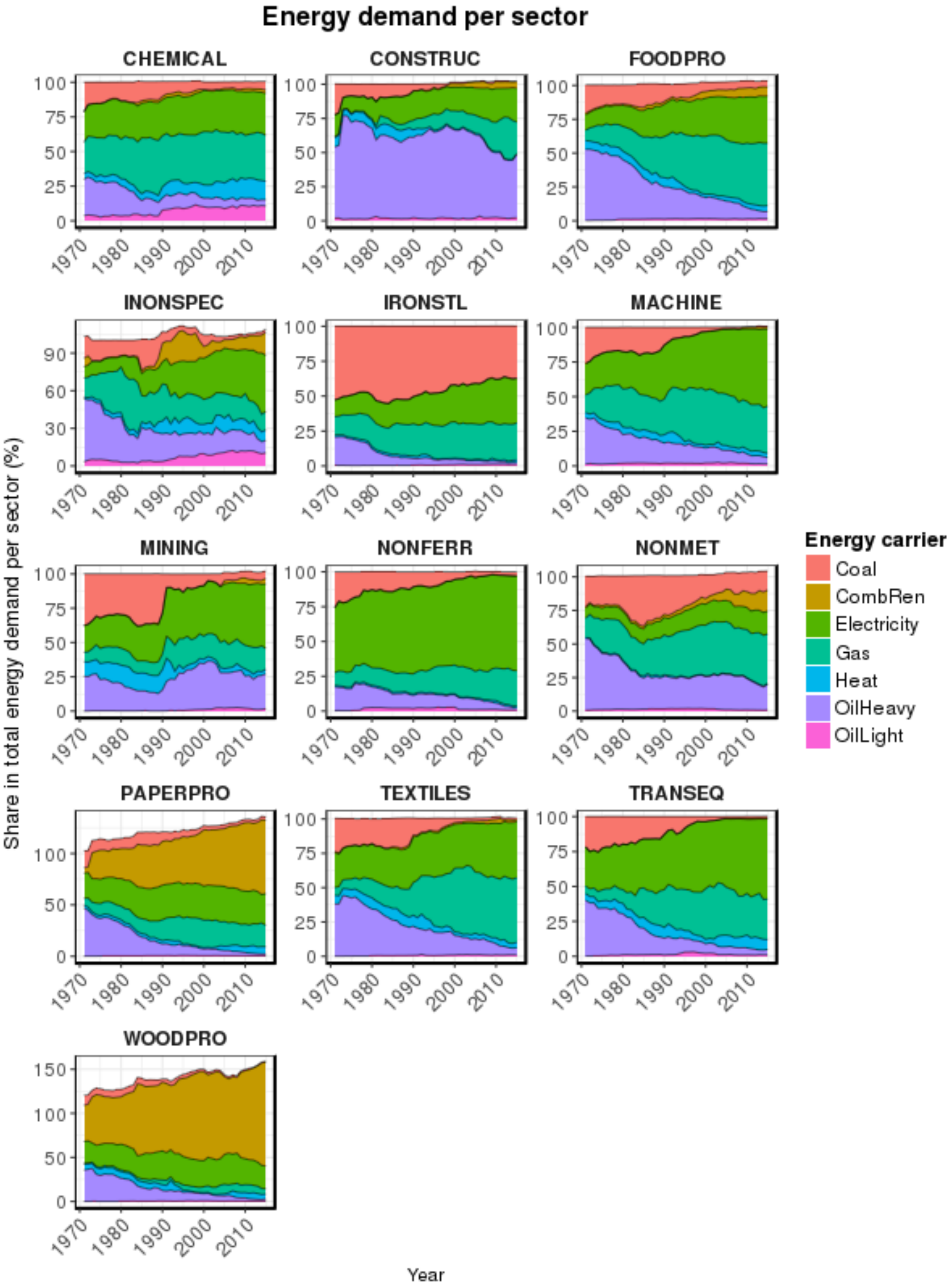

Figure 24 - Overview of energy use per sector in Europe (OECD/IEA, 2017b)

Legend:

- **CHEMICAL:** Chemical and petrochemical sector
- **CONSTRUCT:** Construction
- **FOODPRO**: Food and tobacco
- **INONSPEC**: Non-specified
- **IRONSTL:** Iron and Steel
- **MACHINE:** Machinery
- **MINING:** Mining and quarrying
- **NONFERR:** Non-ferrous metals
- **NONMET:** Non-metallic minerals
- **PAPERPRO:** Paper pulp and printing
- **TEXTILES:** Textile and leather
- **TRANSEQ:** Transport equipment
- **WOODPRO:** Wood and wood products