REINVENT – PROJECT NR 730053

Decarbonisation pathways for key economic sectors

Deliverable 4.3

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1 Introduction

The report at hand describes deep decarbonisation pathways for the steel, plastics and pulp & paper sectors developed in Work Package 4.3 of the REINVENT project. These pathways explore how these energy intensive sectors, which are responsible for a lion's share of the EU's industrial GHG emissions, can become climate neutral by 2050 and how their cumulated emissions by that date can be reduced in order to stay within the limits of a 1.5°C scenario.

Steel, plastics and pulp & paper are three of the four focus sectors in REINVENT. The fourth sector is food, which is not addressed in this report. The reason is that agriculture is not part of the WISEE model and thus the major part of food related emissions could not be addressed. The food sector will however be covered in WP 4.4 based on the Integrated Assessment Model IMAGE by PBL. Previous REINVENT scenario work on food can be studied in the Deliverable 4.2 report.

Within the context of the REINVENT project, WP 4 provides quantitative scenarios, which firstly have the role of creating systemic background knowledge for a) the research of innovation dynamics in WP 2 and 3 and b) about technical potentials of single technologies. A second function of WP 4 is to give insights on the absolute and aggregate potentials of certain strategies and thus provides input to WP 5, which has been designed to assess overall impacts, not only on energy use and emissions but also a range of SDGs.

In WP 4.1 an overview on existing scenario literature as well as industry roadmap was provided and documented in D4.1. Within WP 4.2 PBL and Wuppertal Institute developed scenarios for the four REINVENT focus sectors. The results of the parallel scenario experiments with the Integrated Assessment Model (IAM) *IMAGE* and the bottom-up model *WISEE edm* were analysed and compared in D4.2.

One important result of the comparison was that GHG reductions in the scenarios derived by the WISEE model were indeed lower in 2050 than in the scenarios provided by IMAGE. However, deep reductions came too late and cumulated emissions in the WISEE scenarios exceeded the volumes given by the IMAGE 1.5 degree scenario by far. A core reason for this was the long investment cycles of the existing stock of process technologies in the sectors covered as well as the expected time of availability of technology alternatives to conventional fossil based technologies for bulk materials production. Therefore one target for D 4.3 was to revise the WISEE scenarios in order to analyse options to enable earlier deep reductions and to analyse possible "bridging" technologies.

The aim of WP 4.3 as termed in the project proposal is to "co-create" sector scenarios, involving stakeholders and experts in workshops to develop joint understanding on 1.5°C-compatible scenario storylines. The purpose of these storylines is to provide a consistent story for the combination of several strategy elements. Within the course of the project work in the previous WP 4.2 the research agenda for 1.5°C-compatible scenario storylines to be explored in WP 4.3 and WP 4.4 was specified:

- 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;
- Regional developments;
- 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) as well as carbon sources (biomass, cement plants, polymer waste);
- Material efficiency and service efficiency potentials in the steel and plastics industry.

The WP 4.3 scenarios presented here take this agenda into account. They rely upon the previous modelling efforts in WP 4.2, which served as input for the workshops with stakeholders from the respective industrial sectors and on the results of these workshops. REINVENT WP 3.5 also contributed by providing elaborated qualitative storylines. These inputs were used to build-up a framework of assumptions used to feed the WISEE edm model framework. WISEE edm calculates energy and feedstock use in the core industrial processes. Process substitution is regarded in a vintage stock model approach that regards the age and lifetime of processes and thus provides a realistic background for the simulation of the phase-in of new technologies.

The report at hand starts with an overview on the methodology of scenario development in WP 4.3 describing the inputs and tools used. The actual presentation of the scenarios is given sector-wise in chapters 3 to 5. The quantitative scenarios described are referred to as “cases” indicating that they have been developed in the sector context and not giving an overall consistent and integrated picture of the four focus sectors. Chapter 6 integrates the sector cases and thus provides first order scenarios by combining the sector cases. Here, also regional aspects in regard to overall energy demands are analysed and discussed.

The sector descriptions in chapters 3 to 5 do not provide a full picture of today’s production systems and value chains with their respective technologies as well as the sectors' up- and downstream integration. These systemic issues can be studied in the REINVENT sector reports (deliverables) developed in WP 2.

For these analyses the WISEE edm modelling framework was not integrated into an overall energy system model (containing energy supply also). The scenarios presented can thus not claim to show an optimum in regard to economics, energy efficiency or GHG emissions as there is no feedback loop with energy supply. In WP 4.4, PBL’s IMAGE model will provide scenarios pointing at such societal optima. The aim of WP 4.3 was however to show transition potentials from a bottom-up (i.e. sectoral) perspective.

2 Methodology and Design of the Sector Cases

In order to derive co-created sector scenarios in REINVENT the results of the several WP 4.3 workshop discussions (see below) were transferred into scenario storylines. The parallel qualitative storyline development in Work Package 3.5 has been used as guideline and background information in the workshops and is therefore another important pillar of the cases and scenarios presented in the report at hand. These are the basis for the building of different sector cases, which are described in the following chapters sector by sector.

Wuppertal Institute's WISEE edm modelling framework was used as a tool to derive the quantitative scenario results to describe the several sector cases.

Some of these cases can be considered as stand-alone, meaning that they could be implemented without many cross-sectoral impacts on the other two sectors, others depend on synergies between sectors.

2.1 REINVENT scenario storylines

The storylines developed in REINVENT Work Package 3.5 are an important means to get to consistent combinations of strategies and to derive the "weight" a specific strategy may have in a scenario. The following dimensions have been used to describe the scenarios:

- Technology
- Policies
- Markets
- Finance
- Public pressure

The following scenario storylines have been described in REINVENT WP 3.5:

- Circular Economy
- Demand Management
- Technological replacement
- Process Efficiency

These storylines can be seen as rather prototypical scenarios. A scenario that reaches climate neutrality in all sectors will have to combine several strategies. The modelling in WP 4.3 is intended to assess the different role these strategies may have in the different and differing sectors analysed.

2.2 Co-creation of scenarios (cases) in workshops

The workshop program in WP 4.3 consisted of six workshops:

1. "Modelling" on the role of models in developing scenarios and visions for heavy industry
2. "Food" on a future sustainable nutrition system
3. "Carbon Looping" on the future role of carbon in a circular carbon system
4. "Circular Economy" on the role of secondary production
5. "Electrification" of processes in heavy industry
6. Financing the transition in heavy industry

Workshops 1 was used to mirror industries' own visions on the transition and the role models had and have to derive them. A bottom-up model like WISEE is well in line with the tools used in these contexts and can be used for modelling strategies and also to derive optimal solutions for the sector under a given situation (e.g. a given electricity price). It is not suitable to derive overall optimized solutions for the economy or society as a whole.

Workshops 3 to 5 were used to test storyline elements that had been developed by the project team in advance and also had creative scenario elements. The storyline elements were reality-checked for different dimensions like:

- investment cycles (plant age, technology-readiness level (TRL) of new technologies)
- business opportunities for stakeholders and newcomers
- regional aspects for the uptake of strategies (e.g. existing assets like downstream production assets and pipelines for energy or product supply or renewable potentials, existing networks for recycling etc.)
- regulation frameworks required

Food scenarios discussed in WS 2 are not part of this report but will be an important object of analysis in Work Package 4.4. Results of workshop 6 on financing could not be used for this report as it took place in December 2019 but will be taken up in WP 4.4 and WP 5.

2.3 Building sector cases and model implementation

The aim was not to create ceteris paribus comparisons between different cases showing the effect of single strategies, but to create different internally consistent cases for each of the three sectors. The cases share some common ground like the assumption of a still growing economy. However, economic structures between the cases may still differ: E.g. cases assuming a sharing economy in the mobility sector would have strong implications for the automotive industry whereas in another cases the production volume of cars may follow a business as usual pathway.

The cases are built using four dimensions:

- Adoption of new processes, often called break-through technologies
- Different demand patterns for products with implications for use of GHG intensive products
- The adoption of circular economy strategies
- Creation of a CCS infrastructure for heavy industry with public support

Electrification as well as energy and material efficiency are important strategies throughout all the cases with a high weight respectively.

For **steel and plastics** a *producer driven* case (PD) and a *circular economy driven* case (CE) have been developed respectively.

- The *producer driven* case represents a development were the stakeholders in today’s primary production convert their production stock to produce primary steel and platform chemicals based on renewable feedstock to become climate neutral.
- The *circular economy driven* case (CE) describes a development where regulation (and economics) foster secondary production in the steel and plastics sector and were also the use of materials is reduced by different measures in order to lower the demand for primary materials. Such a development results in lower imports of feedstock and less export of waste to other parts of the world.

The **paper** sector can reduce its emissions from fossil energy carriers rather easily compared to other sectors. A producer driven scenario in such a case would foresee the electrification of steam supply at non-integrated paper mills, i.e. sites with paper machines but without any upstream pulp production. Such a producer driven case would however neglect the potential of the pulping sector to achieve negative emissions either by bio-based energy with carbon capture and storage (BECCS) or by supplying the plastics sectors with sustainable hydrocarbon material (carbon looping). For this reason, for the paper sector a *BECCS case* and a *Carbon Looping (CL)* case were developed.

A CCS driven development in the steel and plastics industry was not part of workshop discussions and has not been modelled in the course of WP 4.3. Respective scenarios developed with PBL's IMAGE and Wuppertal Institute's WISEE model are provided in the WP 4.2 report.

3 Steel

3.1 Producer driven case

3.1.1 Technologies and strategies

The producer-driven new processes (PD) case foresees a clear strategy to establish a carbon neutral production route in primary steel making by introducing hydrogen as a reducing agent to produce DRI, which is afterwards smelted and converted to crude steel in an electric arc furnace (EAF). Other technologies to achieve deep reductions involving electrolysis or CCS are not applied in this case.

DRI thus becomes the core strategic intermediate product. It may be transported over long distances, e.g. between mining and steel making sites (see deliverable D4.5). In our case we assume that DRI is produced in Europe. Otherwise the bulk of energy needed for steel making would just be transferred beyond the system boundary. It could however turn out as a sensible solution in the long run to import reduced material from countries with iron ore resources and abundant renewable energy potentials like Australia, Brazil or Canada. Sweden's iron ore resources are limited but it could take such a role to some extent within the European Union and could be a forerunner in this respect.

Table 1 gives a comparison of the DRI route compared to the blast furnace route. According to our calculations DRI with natural gas could phase in as soon as the CO_2 price reaches a level of 60 EUR/t.

The later conversion to H-DRI, i.e. the substitution of the reducing agent in existing plants, comes at higher CO_2 mitigation costs. A CO_2 price of 160 EUR/t will probably be needed to enable a phase-in by the instrument of a CO_2 price, mainly depending on future prices for natural gas and hydrogen.

Table 1: Overview on existing production routes and new technologies [source: own compilation based on Schneider et al. (2019), Hölling et al. (2017), BCG/VDEh (2013), Croezen/Korteland (2008)]

process	TRL	raw material	reducing agent	emission sources	relevance today in EU production [Mt crude steel/a] in 2015	energy use [GJ/ t crude steel]	CO_2 [t CO_2/ t crude steel]
blast furnace – blast oxygen furnace (BF-BOF) route	9	iron ore / up to 17% scrap	coke (from coking coal) pulverized coal	emissions from the use of BF and BOF gas as well as coke oven gas lime production limestone use	97.2	19 GJ (coal)	1.70
electric arc furnace (EAF) route / scrap based	9	scrap	not required	anode airburn, lime production, coal use in EAF for slag foaming	61.5	2.2 GJ (electricity)	0.08
DRI-EAF route / natural gas based	9	iron ore / flexible in adding scrap	CO / H_2	emissions from CO oxidation in the DRI reactor EAF anode airburn, lime production	3.7***)	10 GJ (natural gas) 2.2 GJ (electricity)	0.60
DRI-EAF route / H_2 based	4-5	iron ore / flexible in adding scrap	H_2 (+ some CO)	EAF anode airburn, lime production	—	7.5 GJ (hydrogen) 3.4 GJ (electricity)	0.05
smelting reduction (HISARNA) + BOF	4-5	iron ore / up to 17% scrap in BOF	coal	emissions from HISARNA reactor and from BOF gas use*), lime production	-****)	12.5 GJ (coal) 0.5 GJ (electricity)	1.20

*) BF slag is a cement clinker substitute. The production of cement clinker is highly emission-intensive.

**) Emissions from the HISARNA reactor could be captured. BOF gas is a by-product from the steelmaking process. If it is used energetically CO_2 emissions occur as well.

***) DRI production in the EU amounts to only 0.6 Mt annually, but the use of imported DRI in EAF has been accounted here as well.

****) One pilot, not running continuously.

Circular economy plays an important role in this case. This is however not due to a clear preference of today's primary steel makers but due to economics. As primary steel making becomes more and more expensive over time the use of scrap as a resource becomes more attractive and potentials that are not used today due to higher sorting efforts and costs become economically viable (see deliverable D4.4). This goes along with a reduction in European scrap exports.

Little advances in material efficiency and reduction of steel demand compared to a business-as-usual pathway are achieved by reducing the amounts of production scraps by more efficient production.

3.1.2 Demand for steel products

Steel demand is not currently modelled in the WISEE model. In IMAGE, it is projected based on historical per-capita consumption and per-capita GDP data, providing a (static) estimate for future crude steel demand. In order to be able to take into consideration the potential effects of increased material circularity and demand-side measures on overall steel production (and, consequently, the carbon emissions resulting from it), it is necessary to decouple consumption volumes from GDP. For this purpose, results from the 2019 study "Industrial Transformation 2050. Pathways to Net-Zero Emissions from EU Heavy Industry" by Material Economics et al. ("IT50 study"), for which the Wuppertal Institute collaborated with Material Economics and the VUB Institute for European Studies, were consulted and analysed.

In the IT50 study, a dynamic materials flow analysis (MFA) model approach based on that by Pauliuk et al. (2013) is used to model future demand for steel. This type of model takes a stock- rather than a consumption-based perspective on demand, arguing that the existing stock of steel products (buildings, bridges, vehicles, etc.) is what provides the actual service to society, whereas the consumption of steel merely serves to build up and maintain that stock. Based on observations in developed countries, it is assumed that mature economies reach a saturation point in terms of per-capita steel stock once urbanisation and infrastructure development are completed. For the EU, the IT50 study expects a saturation level of 13.7 tons per capita to be reached by the 2040s in a business-as-usual scenario (up from 11.9 t per capita in 2017). Total steel demand is therefore determined by population forecasts, expected per-capita stock developments (as an indicator for *new* stock build-up), and product lifetimes (as an indicator for the replacement of *existing* stock). Taking into account in-use stock and average product lifetimes also makes it possible to estimate future availability of end-of-life steel scrap, allowing for predictions on the potential level of secondary steel production (under consideration of scrap collection rates and remelting losses). Also included in the model is the formation of *new* scrap during manufacturing. While this scrap is not lost (almost 100% is recycled), it does increase the overall volume of steel required to meet demand at a given time (and decreasing scrap formation can thus *reduce* steel demand) (Material Economics et al. 2019; Pauliuk et al. 2013; Daehn et al. 2016a).

A baseline trajectory assumes a continuance of current practice, i.e. no demand-side reductions through improved material efficiency or circular economy measures. Patterns of use are thus similar to today, so that per-capita steel demand follows the trajectory described above, growing at an annual rate of around 0.6% (15% overall) and reaching 13.7 tons by the 2040s. In part, this increase accounts for the development of a low-carbon energy system and the required infrastructures. The baseline scenario serves as a jumping-off point for steel demand in the two cases analysed in this report. It is thus not analysed separately.

In a producer-driven case, steel demand follows largely the baseline trajectory, with the exception of savings achieved through material-efficient production (i.e. a reduction in new scrap formation during manufacturing). In 2050, this cuts total annual steel demand by roughly 12 Mt when compared to a baseline scenario, down to 181 Mt. Meanwhile, patterns of use do not deviate from the baseline.

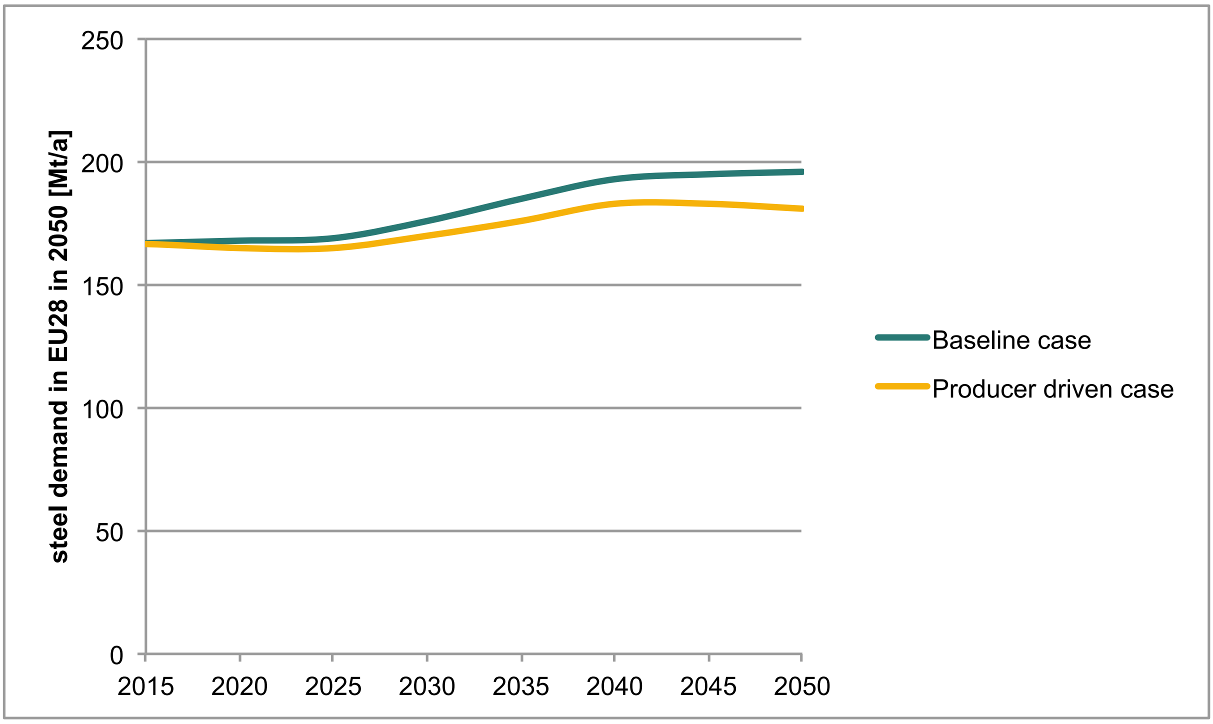


Figure 1: Total steel demand in 2050 in the EU in the PD case compared to the baseline [source: own graphic, based on Material Economics et al. 2019]

EU steel demand is modelled for four end-use sectors: construction, transport (i.e. vehicles like cars and trains as well as ships), machinery, and metal products (including appliances, packaging and other consumer goods). The biggest relative savings through material-efficient production are achieved in the products segment (14%), while the largest absolute savings occur in steel use for transportation (5 Mt/a).

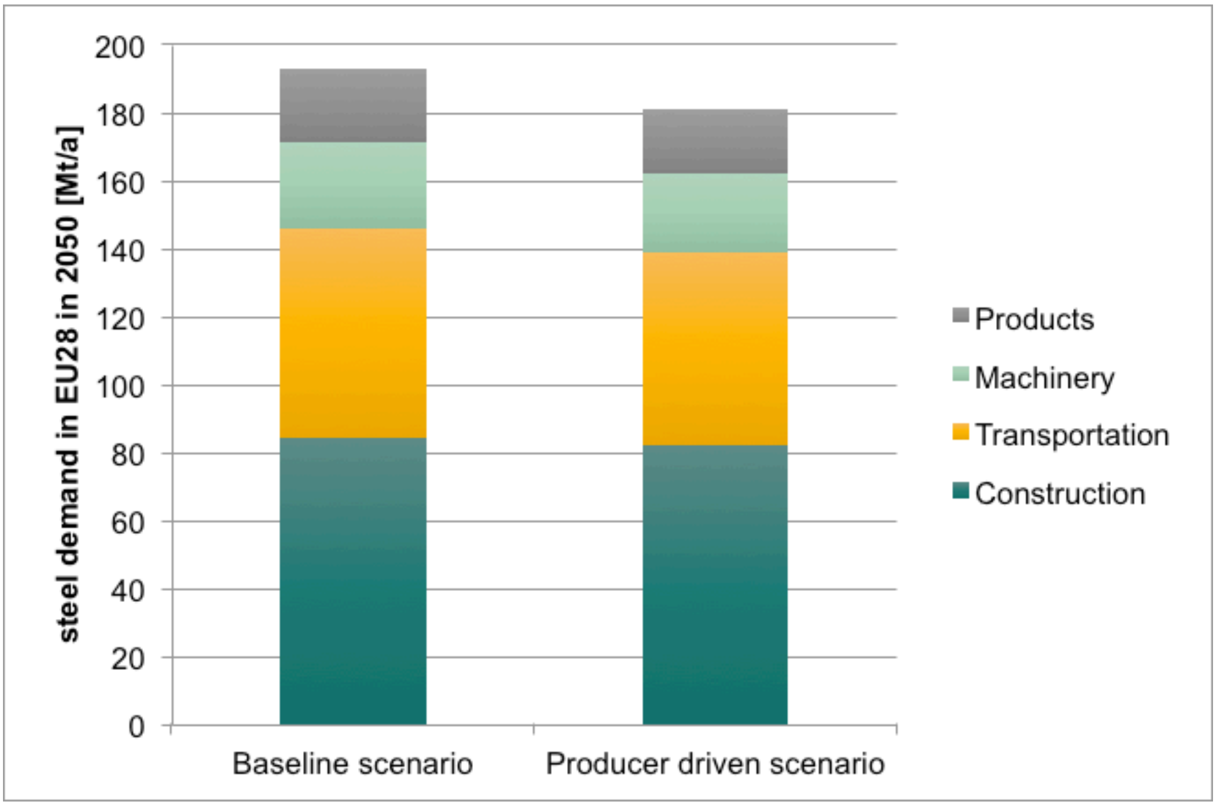


Figure 2: Steel demand from key sectors in 2050 in the EU [source: own graphic, based on Material Economics et al. 2019]

As steel stocks continue to grow, so does the availability of end-of-life scrap. This opens up possibilities for meeting an increasing share of steel demand with secondary steel produced in electric arc furnaces (EAF). Even without more significant demand reductions, secondary steel exceeds primary steel well before 2050.

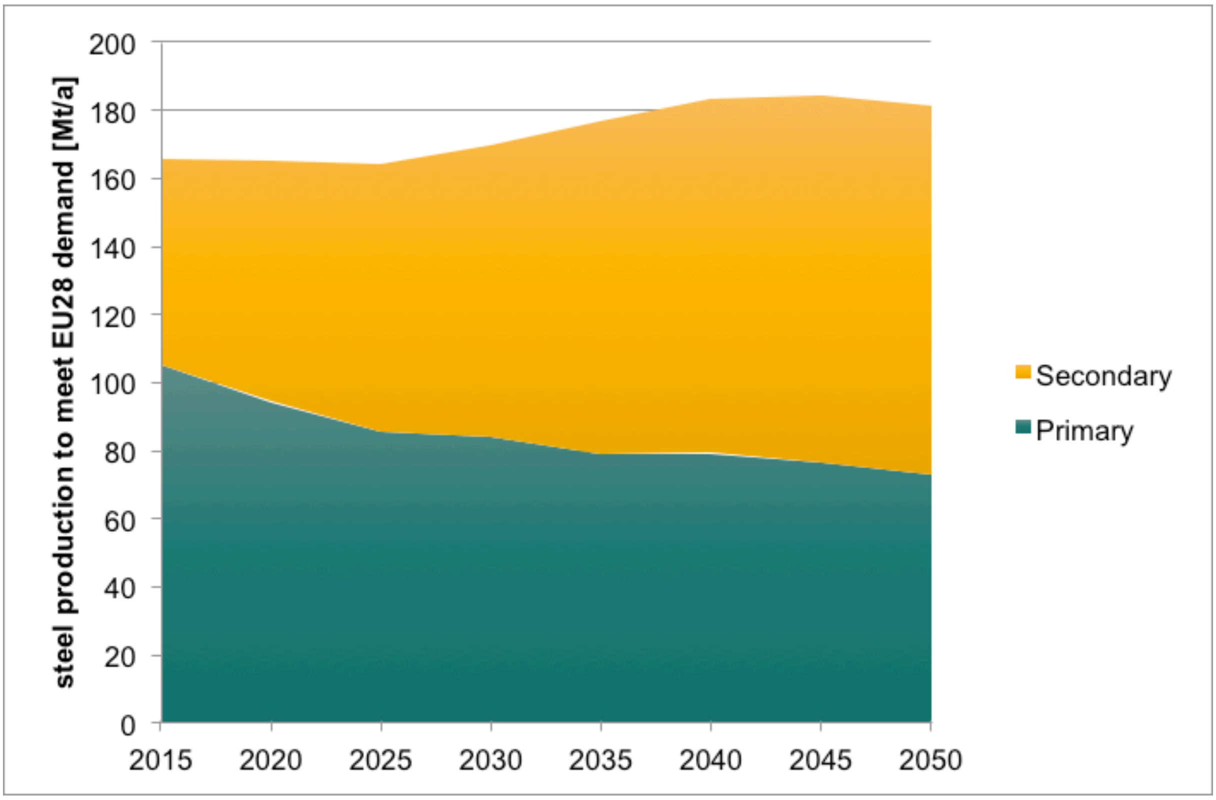


Figure 3: Development of primary and secondary production to meet EU steel demand [source: own graphic, based on Material Economics et al. 2019]

This is not without challenges, as the share of secondary steel becomes increasingly constrained by quality rather than by availability. The IT50 study finds that even in non-circular scenarios, available steel scrap could cover EU demand by 2050 if quality issues are not taken into account. Copper contamination of end-of-life scrap is already problematic today, leading to secondary steel being used largely for purposes with a high copper tolerance (especially rebar) and/or diluted with pig iron to become suitable for more demanding applications.

To verify whether this constraint is reflected accordingly in the scenario, 2050 production volumes for primary and secondary route were compared to the copper tolerances of the intermediate products going into each of the four end-use sectors, as described in Daehn et al. 2016b. The required qualities were compared to the expected copper contents of BOF (0.02 wt %) and EAF (0.15 wt %) steel. The latter value represents a production based on today's average scrap flows in each of the end-use sectors. Products with a tolerance below 0.15 wt % would thus not be possible to be produced through the EAF route and are marked orange in Table 2.

The numbers compared favourably so that in the producer driven scenario, EAF steel could be used where possible by today's standards (intermediate products with a copper tolerance of 0.15 wt % or more), while primary steel would be used for the rest (i.e. higher-tolerance products as well as cast iron and steel, where copper does not have the same metallurgical effects). This adds up to 108 Mt of secondary and 73 Mt of primary steel in 2050. It should be noted that this is a basic comparison to test general feasibility of EAF/BOF volumes, and that the numbers regarding copper contents taken from Daehn et al. are global averages based on sources representing a range of regions and time periods. Furthermore, it does not account for changes in copper concentration in end-of-life scrap, which could increase through accumulation as well as decrease through improved disassembly, shredding and sorting. Copper tolerances of certain intermediate products may also improve through efforts in casting and processing (Daehn et al. 2017b).

Table 2: Copper tolerance and demand volume of intermediate products for the four end-use sectors in the PD case [source: own table, based on Daehn et al. 2017b & Material Economics et al. 2019]

End-Use Sector	Intermediate Product	Product	Estimated Cu Tolerance (wt %)	Share of Sector Volume (%)	Demand Volume 2050 (Mt/a)
Vehicles	Bars	Wire Rod	0.1	7	4.1
		Hot Rolled Bar	0.15	11	6.2
	Flat/ Plates	Plate	0.15	19	11.1
		Hot Rolled Coil	0.15	4	2.5
		Cold Rolled Coil Galvanized	0.06	42	23.8
	Tubes	Welded Tube	0.15	1	0.4
		Seamless Tube	0.15	4	2.5
	Castings	Cast Iron	-	12	7
Industrial equipment	Shapes	Rail	0.15	1	0.1
	Bars	Wire Rod	0.1	5	1
		Hot Rolled Bar	0.15	20	4.7
	Flat/ Plates	Plate	0.15	17	3.9
		Hot Rolled Coil	0.1	17	3.9
		Cold Rolled Coil	0.06	11	2.5
		Electrical Sheet	0.06	5	1
	Tubes	Welded Tube	0.15	11	2.6
		Seamless Tube	0.15	2	0.5
	Castings	Cast Iron	-	9	2
		Cast Steel	-	3	0.7
Construction	Shapes	Light Section	0.3	7	5.8
		Heavy Section	0.3	6	5.2
		Rail	0.3	2	1.2
	Bars	Rebar	0.4	28	22.7
		Wire Rod	0.15	13	10.6
		Hot Rolled Bar	0.2	1	0.6
	Flats/ Plates	Plate	0.15	1	0.8
		Hot Rolled Coil	0.2	15	12.1
		Hot Rolled Coil Galvanized	0.2	2	1.2
		Hot Rolled Narrow Strip	0.2	3	2.5
		Cold Rolled Coil	0.1	10	8.3
	Tubes	Welded Tube	0.15	6	5.1
		Seamless Tube	0.15	3	2.2
	Castings	Cast Iron	-	5	3.7
Products	Bars	Wire Rod	0.1	21	4.1
		Hot Rolled Bar	0.15	16	3.1
	Flat/ Plates	Plate	0.15	14	2.7
		Hot Rolled Coil	0.1	3	0.6
		Hot Rolled Narrow Strip	0.1	8	1.6
		Cold Rolled Coil	0.06	16	3.1
		Cold Rolled Coil Coated	0.06	7	1.3
		Cold Rolled Coil Tinned	0.06	5	0.9
	Tubes	Welded Tube	0.15	1	0.1
	Castings	Cast Iron	-	5	1
		Cast Steel	-	3	0.5

Currently, demand for steel with low levels of copper contamination (<0.15%) accounts for around 32% of total demand (51 Mt in 2017). In a producer-driven scenario, demand for steel with a copper content of under 0.15% would see an increase of 5 Mt over the next decades, reaching a total of 56 Mt by 2050. While this still accounts for around 31% of total steel demand, it demonstrates the potential of a more material-efficient production when compared to a baseline scenario. Without reductions in scrap formation this increase would be twice as high, with a growth of 10 Mt and a total demand of 61 Mt in 2050 when following a business-as-usual pathway.

3.1.3 Modelling results

The conversion of Europe's coal based blast furnace/blast oxygen furnace (BF/BOF) plants to DRI and scrap based sites was modelled with WISEE edm. Figure 1 shows the phasing-out of the BF/BOF route over time and the parallel phasing-in of DRI plants.

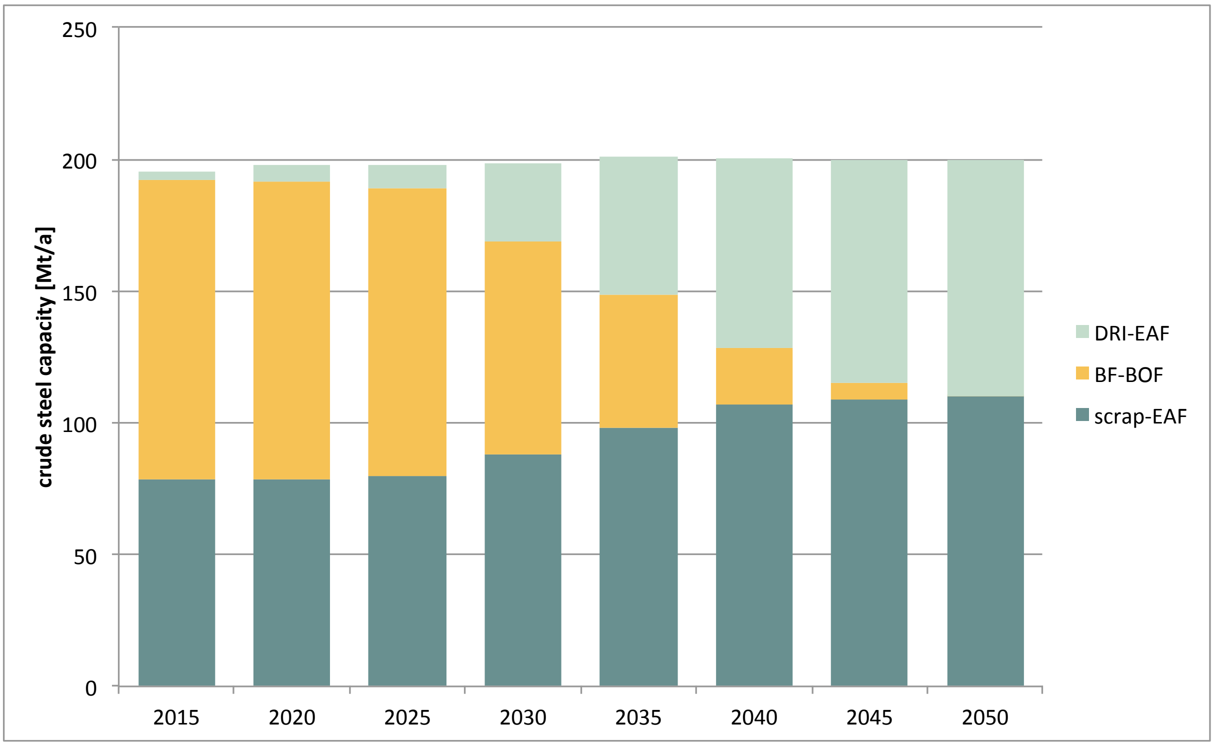


Figure 4: crude steel capacities in the PD case [source: own calculations]

In the PD case producers convert the existing sites and simultaneously keep up the original capacities. Blast furnaces are retrofitted in Western Europe until 2025, after 2025 the replacement by the DRI route starts. In the countries of the Visegrád group the existing coking-coal mines in the Upper Silesian Coal Basin as well as scepticism towards natural gas imports postpone the introduction of DRI based production to the period after 2030.

Figure 5 displays the development of energy use. The EAF route gains massively in share from 2025 on requiring additional electricity. DRI is produced in the beginning mainly from natural gas. Hydrogen as reducing agent is however phased-in from the beginning, reaching a share of finally 90% in reducing agent use in 2050.

A challenge of this scenario is the "use curve" for natural gas use: There is a sharp rise in use, a peak in 2040 and a sharp decline again afterwards. On the level of the gas transport grid this should not be an issue because there are large redundancies at the moment on the hand and on the other hand other natural gas use (in particular in the building sector) will decline. At the site level however this "natural gas bridging" causes extra infrastructure efforts and several adaption steps over time.

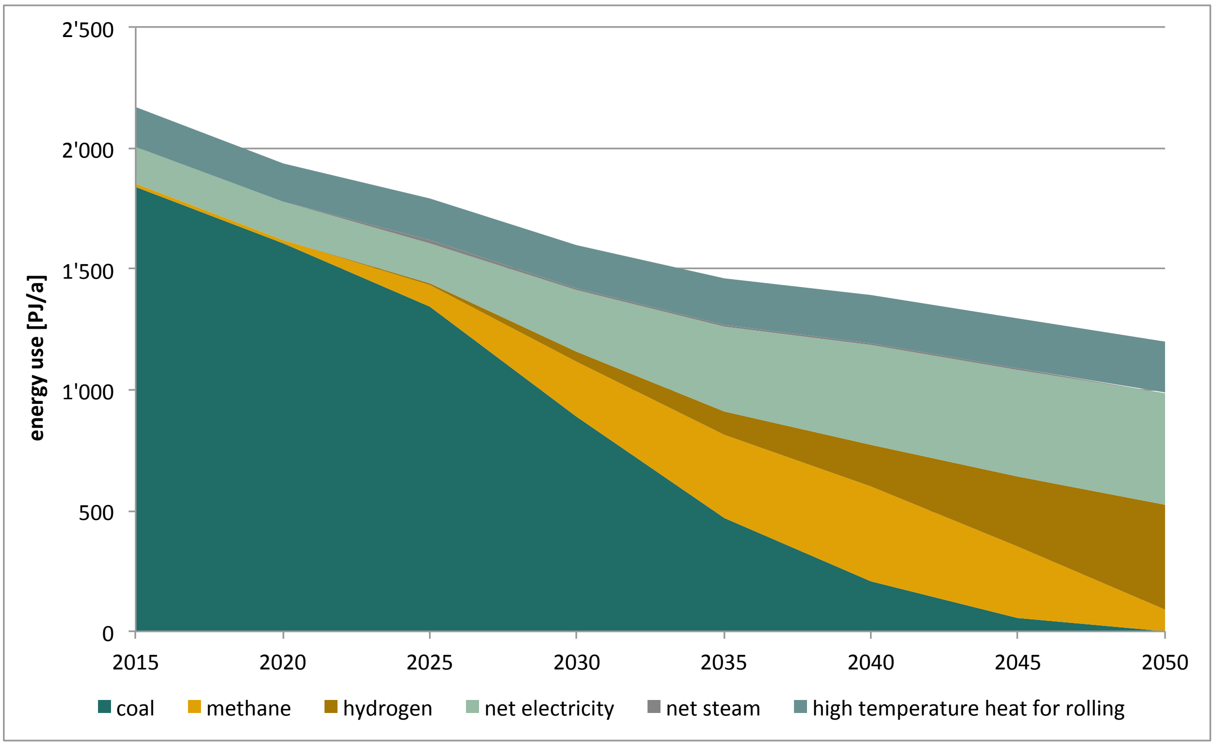


Figure 5: Energy use in steel making in the PD case [source: own calculations]

In 2050 the energy demand for steel making includes 434 PJ of hydrogen and 462 PJ of electricity. The demand for methane as an additional reducing agent is 87 PJ and the demand for energy to heat up crude steel in reheating furnaces for hot rolling reaches 212 PJ. Coal is still used in EAF to produce a proper slag (27 PJ).

Figure 6 shows the steel related CO_2 emissions in the EU28. Almost 40% of CO_2 reduction may be achieved in such a producer driven scenario by the introduction of new production processes and a shift to secondary production until 2030. Natural gas use based DRI production allows for a 50% reduction compared to the BF/BOF route allowing for a massive GHG reduction.

Until 2050 a reduction of 94% can be achieved by converting the whole primary steel production stock and the phase-in of hydrogen. However, such a deep reduction requires also a total substitution of natural gas use in the DRI plants as well as the hot rolling stoves. In the DRI plants bio-methane could be used, whereas in the rolling plants also hydrogen or the direct use of electricity would be alternatives. Individual solutions will probably depend on local resource availability and grid conditions.

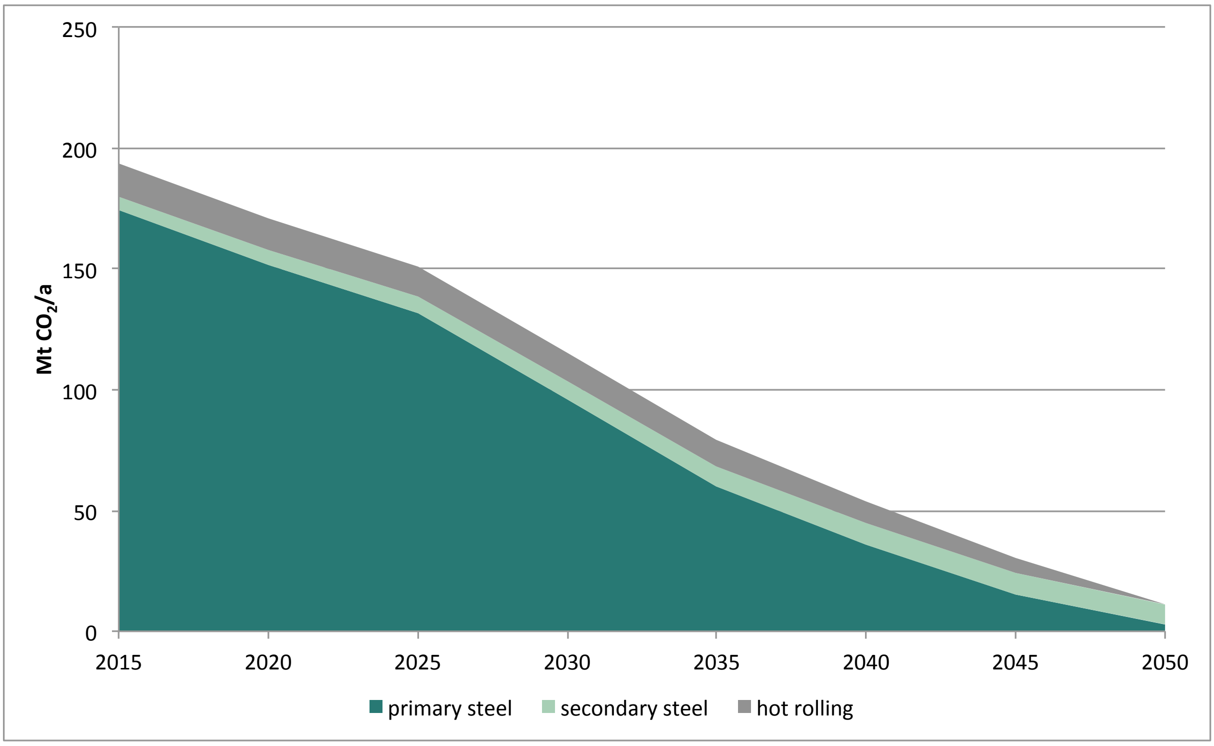


Figure 6: CO_2 emissions in steel making in the PD case [source: own calculations]

A 100% GHG reduction in the steel sector will be feasible if anode material and coal use in EAF is based on biogenic carbon sources like char coal.

3.2 Steel in a Circular Economy

3.2.1 Technologies and strategies

Technologies used in the CE case for the production of steel do not differ from the ones described for the PD case, so the decarbonisation of primary production is achieved by hydrogen direct reduction.

However, steel demand decreases significantly compared to today and compared to the pathway described in the PD case. Savings in this scenario are not only achieved by more efficient production but also by addressing consumer demand for products containing steel like buildings or cars. The savings are described in more detail in the following section.

Like in the PD case, secondary production is also augmented and quality steel products are produced more and more on the basis of excellently sorted steel scrap. Due to the smaller steel stock annual scrap flows (e.g. from cars) are lower as in the PD case.

3.2.2 Demand for steel products

In a circular economy case, steel demand is reduced not only on the production side (through decreased scrap formation in manufacturing), but also on the demand side. Consequently, the central assumption that per-capita steel stocks climb to a level of around 13.7 Mt and then saturate is no longer held. Instead, the ways in which we use steel, and the products and structures made from it, are expected to change over the coming decades. A wide range of demand-side opportunities are seized so that less material input can yield the same economic benefits. Key strategies identified include material efficiency, sharing business models and increased product lifetimes (e.g. through design for reuse of steel components). The IT50 study finds that in an ambitious circular scenario, an additional 42 Mt steel per year can be cut this way in 2050. The circular economy scenario is the only one of the scenarios analysed here in which demand is *lower* in 2050 than it is today (Material Economics et al. 2019).

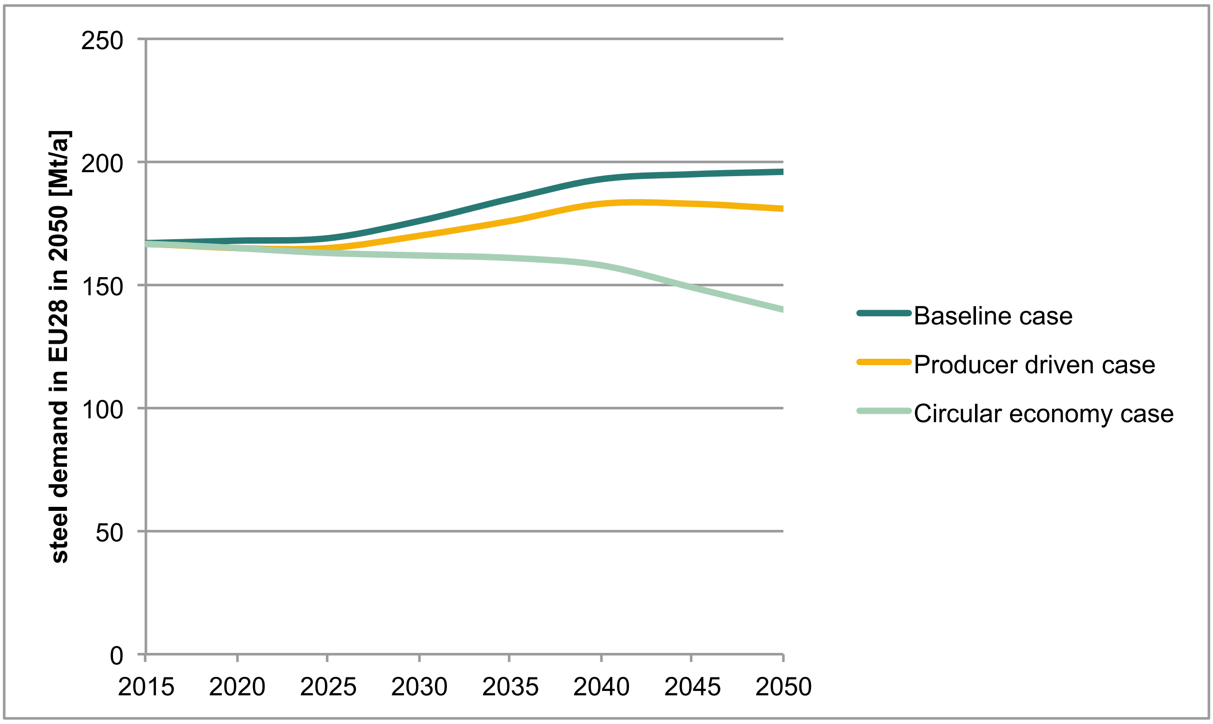


Figure 7: Total steel demand in 2050 in the EU in the CE case compard to PD and baseline [source: own graphic, based on Material Economics et al. 2019]

Different measures are incorporated for each of the four end-use sectors:

(1) Construction

Currently, there is a significant overuse of steel in buildings: As much as half of the material used could be saved by reducing over-specification. Similarly, lightweight design using high-strength materials can lead to considerable savings in both buildings and infrastructure. Improved floor space utilisation, extending building lifetimes and re-using buildings and building components can further reduce material demand. Even in assuming that this potential is only partially exploited (around half the potential identified for buildings), demand-side measures lead to savings of around 16 Mt in 2050 in construction alone.

(2) Transportation

In the transport segment, the biggest demand-side opportunity lies in reducing the number of passenger cars through sharing schemes. Busses and trucks can be used more intensely, their design optimised and lifetimes extended. The use of high strength steel increases material efficiency for trains and boats. Overall, a reduction potential of about 15 Mt is achieved through demand-side measures in transportation.

(3) Machinery

The use of high strength steel can reduce the material intensity of machinery by around 10%, such as industrial and manufacturing equipment, power plants, as well as mobile equipment (e.g. for mining, agriculture). A total reduction in steel demand from machinery of around 2 Mt is achieved this way.

(4) Products

The sharing economy plays a role not just for passenger cars but for other steel-containing consumer goods, too, e.g. through sharing schemes for domestic appliances. There is also some potential in the reduction of packaging. Overall, around 3 Mt of steel can be saved through demand-side measures in the products segment.

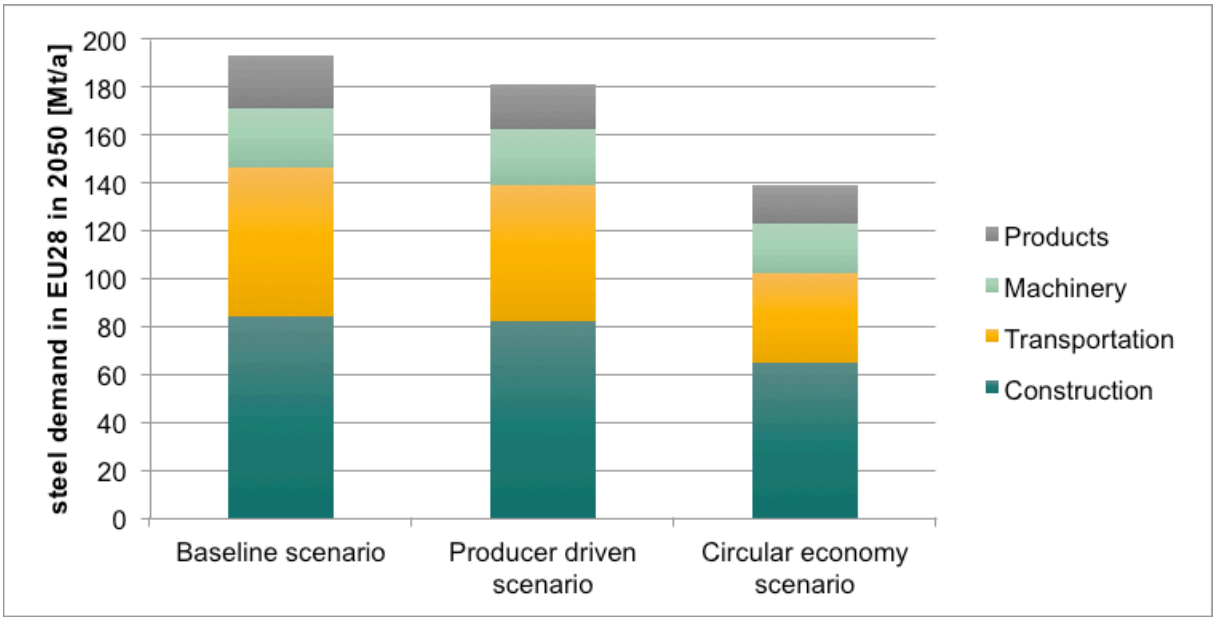


Figure 8: EU steel demand from key sectors in 2050 [source: own graphic, based on Material Economics et al. 2019]

In a circular economy scenario, strategies for increasing materials recirculation for secondary production are applied. This includes improvements in product design, end-of-life disassembly, scrap collection rates, and scrap handling, to reduce copper contamination and other tramp elements. As a result, as much as 70% (97 Mt) of annual steel demand is met with recycled steel in 2050.

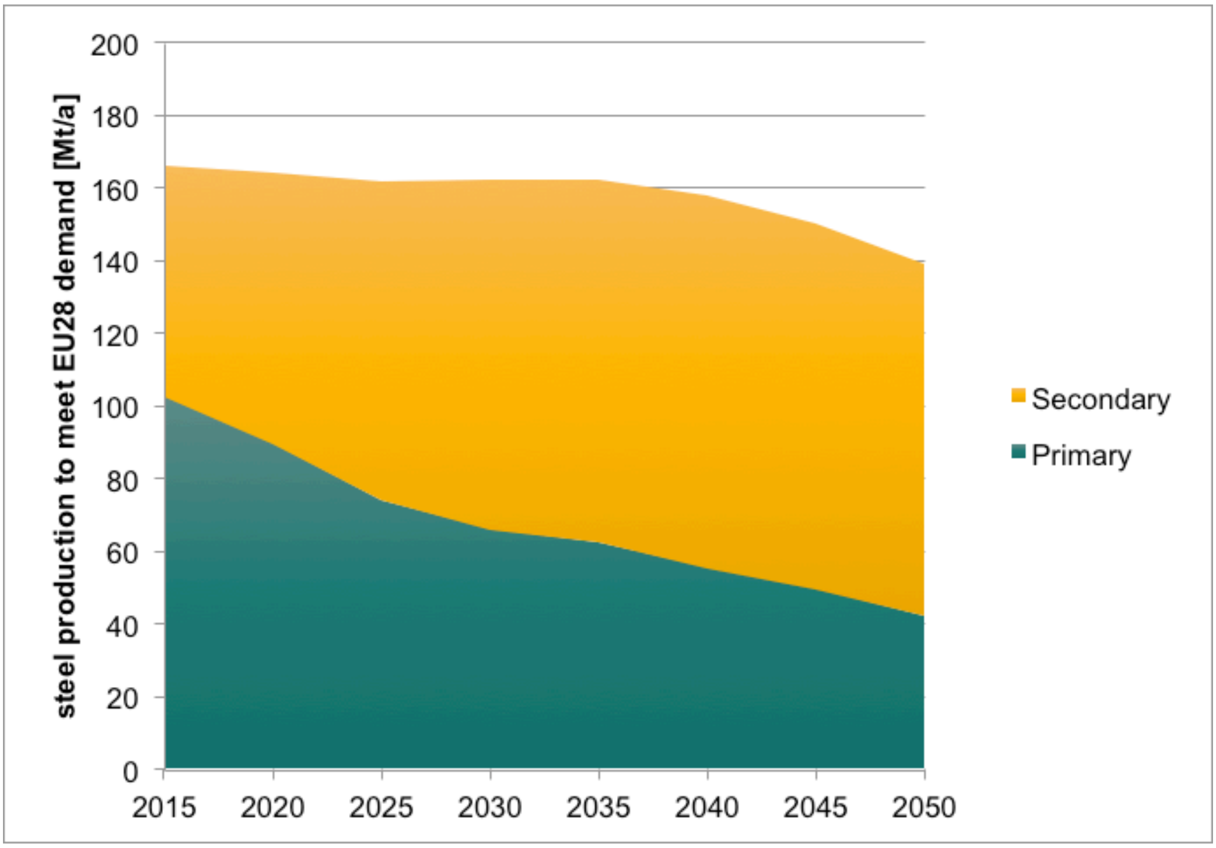


Figure 9: Steel produced through the primary and secondary routes to meet EU steel demand 2015-2050 [source: own graphic, based on Material Economics et al. 2019]

When again comparing production volumes with copper contents and tolerances of intermediate products as specified by Daehn et al. (2016b), the numbers match even if one assumes that tolerances are not increased and the measures taken to decrease copper contamination serve only to maintain current contamination levels of around 0.15% in EAF steel. The 42 Mt of primary steel produced in 2050 would just about cover the production of low-tolerance intermediate products (marked orange in Table 3). Higher-tolerance products as well as cast iron and steel would need to be produced entirely through the secondary route.

Table 3: Copper tolerance and demand volume of intermediate products for the four end-use sectors in the CE case [source: own table, based on Daehn et al. 2017b & Material Economics et al. 2019]

End-Use Sector	Intermedi-ate Product	Product	Estimated Cu Tolerance (wt %)	Share of Sector Volume (%)	Demand Volume 2050 (Mt/a)
Vehicles	Bars	Wire Rod	0.1	7	2.7
		Hot Rolled Bar	0.15	11	4
	Flat/Plates	Plate	0.15	19	7.2
		Hot Rolled Coil	0.15	4	1.6
		Cold Rolled Coil Galvanized	0.06	42	15.4
	Tubes	Welded Tube	0.15	1	0.3
		Seamless Tube	0.15	4	1.6
	Castings	Cast Iron	-	12	4.5
Industrial equipment	Shapes	Rail	0.15	1	0.1
	Bars	Wire Rod	0.1	5	1
		Hot Rolled Bar	0.15	20	4.3
	Flat/Plates	Plate	0.15	17	3.6
		Hot Rolled Coil	0.1	17	3.6
		Cold Rolled Coil	0.06	11	2.3
		Electrical Sheet	0.06	5	1
	Tubes	Welded Tube	0.15	11	2.4
		Seamless Tube	0.15	2	0.5
	Castings	Cast Iron	-	9	1.8
		Cast Steel	-	3	0.6
Construction	Shapes	Light Section	0.3	7	4.6
		Heavy Section	0.3	6	4.1
		Rail	0.3	2	1
	Bars	Rebar	0.4	28	18
		Wire Rod	0.15	13	8.4
		Hot Rolled Bar	0.2	1	0.4
	Flats/Plates	Plate	0.15	1	0.7
		Hot Rolled Coil	0.2	15	9.6
		Hot Rolled Coil Galvanized	0.2	2	1
		Hot Rolled Narrow Strip	0.2	3	2
		Cold Rolled Coil	0.1	10	6.5
	Tubes	Welded Tube	0.15	6	4
		Seamless Tube	0.15	3	1.7
	Castings	Cast Iron	-	5	2.9
Products	Bars	Wire Rod	0.1	21	3.4
		Hot Rolled Bar	0.15	16	2.6
	Flat/Plates	Plate	0.15	14	2.3
		Hot Rolled Coil	0.1	3	0.5
		Hot Rolled Narrow Strip	0.1	8	1.4
		Cold Rolled Coil	0.06	16	2.6
		Cold Rolled Coil Coated	0.06	7	1.1
		Cold Rolled Coil Tinned	0.06	5	0.7
	Tubes	Welded Tube	0.15	1	0.1
	Castings	Cast Iron	-	5	0.8
		Cast Steel	-	3	0.5

In a circular economy case, demand for steel with a copper content of under 0.15% would decrease by 9 Mt over the next decades, to 42 Mt in 2050. While this still accounts for around 30% of total demand, 2050 demand for steel with low copper tolerances would be 19 Mt less (-31%) than on a business-as-usual pathway, and 14 Mt less (-17%) than in the other two scenarios.

3.2.3 Modelling results

The Circular Economy case in the steel sector comes along with a reduction in capacities for primary steel making and also for rolling. The challenge is to reduce and convert simultaneously. Figure 10 shows the development. After 2020 there are no more retrofits in blast furnaces because existing overcapacities and shrinking need for primary steel require capacity alignment. Phase-in of DRI in primary steel making starts in 2025 (like in the PD case described above).

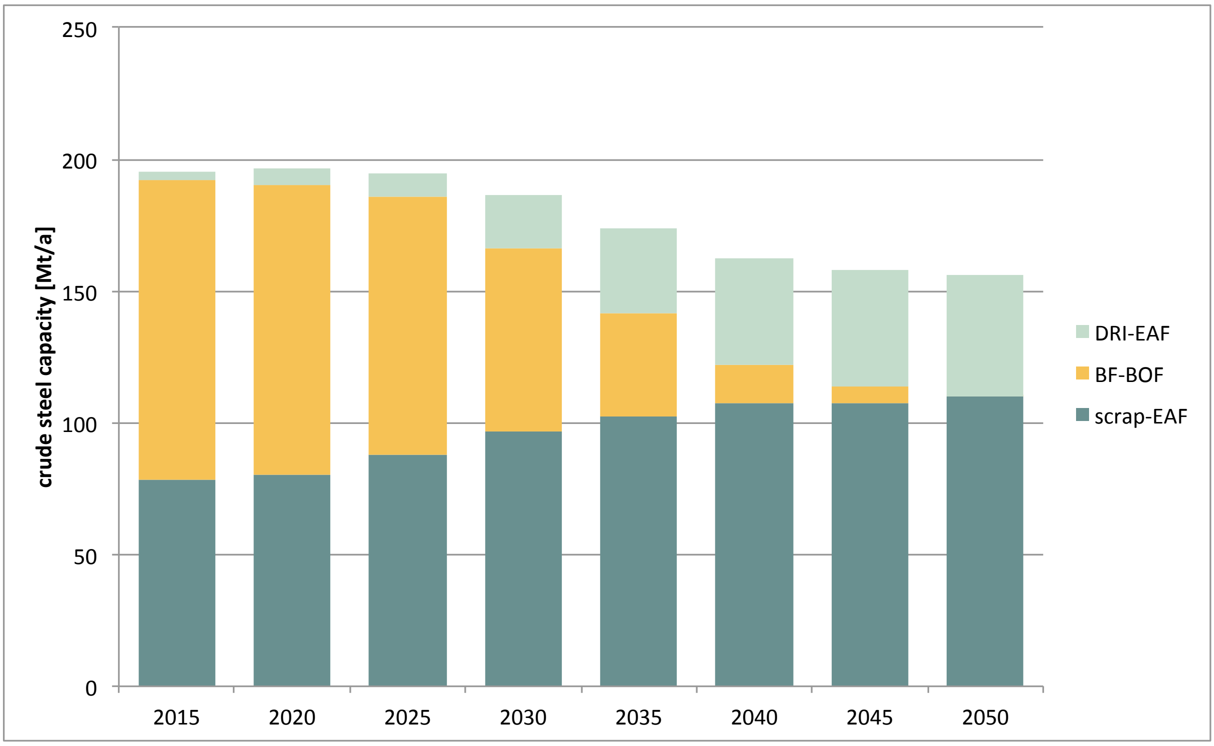


Figure 10: crude steel capacities in the Circular Economy case [source: own calculations].

New investment in EAF capacities is almost completed in 2040 with only some smaller amendments following until 2050 in MEE countries.

Energy use in the steel sector is reduced massively in the CE case, with reductions by 36% in 2030 compared to 2015 and by 64% by 2050. The respective values in the PD case are 24% (2030) and 34% (2050). Even if we assume that not only reducing agent demand but also high temperature heat in rolling will be supplied by hydrogen the savings are still at 56% in 2050 if the respective energy losses in the production of hydrogen (efficiency of 75% assumed) are regarded.

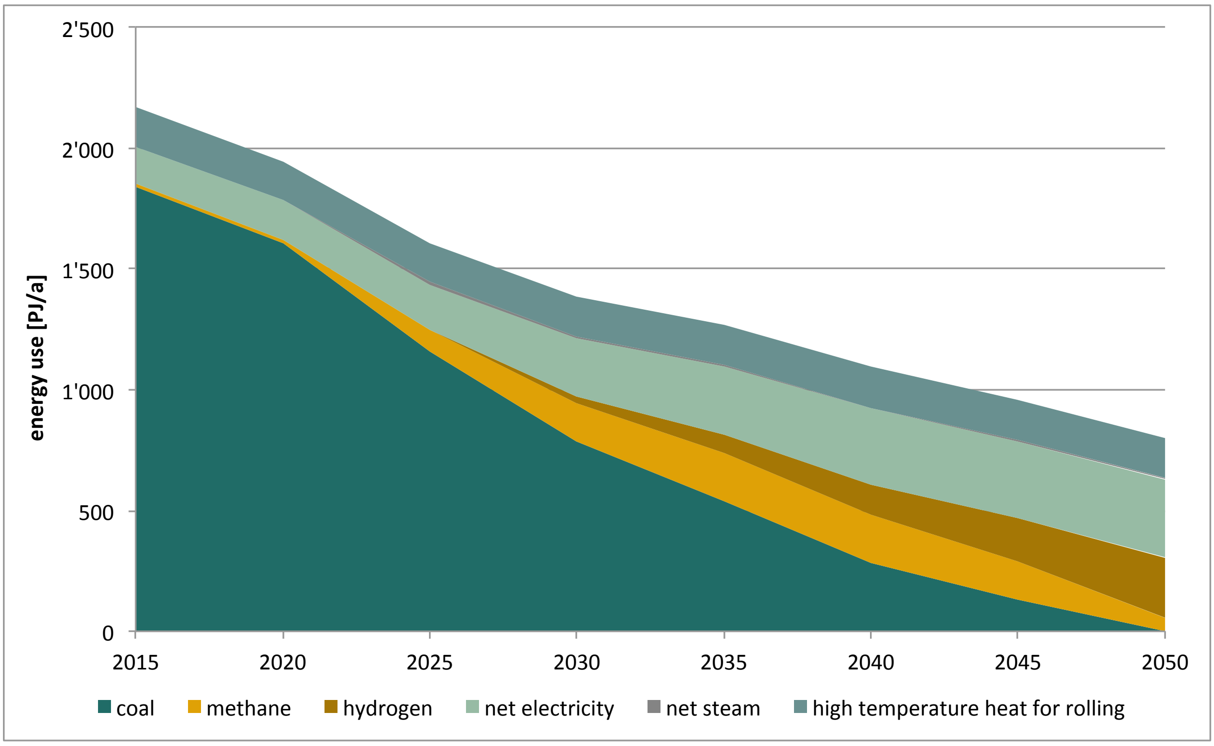


Figure 11: energy use in steel making in the CE case [source: own calculations]

Hydrogen demand as reducing agent amounts to 250 PJ in 2050 with an additional methane demand of 56 PJ. Electricity demand reaches an annual amount of 324 PJ (vs. 462 PJ in the PD case). Due to absolute lower steel volumes the high-temperature heat demand for hot rolling is also considerably lower than in the PD case (162 vs. 212 PJ/a).

The CO_2 reduction pathway is very similar to that described for the PD case: Figure 12 shows an almost 50% reduction until 2030 and a reduction by 95% in 2050 - with the option to get to full carbon neutrality with additional biogenic carbon use in EAFs.

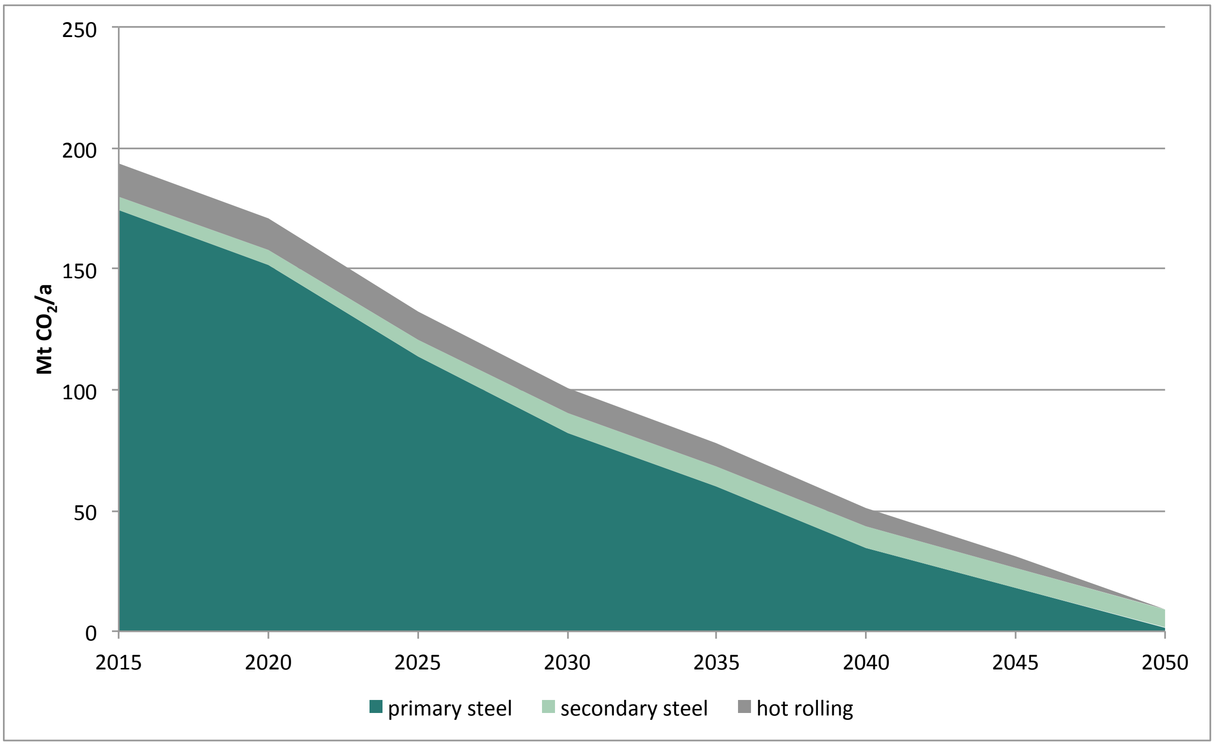


Figure 12: CO_2 emissions in steel making in the CE case [source: own calculations]

4 Plastics

A focus on further development in Work Package 4.3 has been the development of new scenarios for the plastics sector. For the steel and the pulp and paper sector there are rather clear visions on a possible decarbonized (and non-fossil) future. The plastics sector, however, with its inherent use of hydrocarbons, poses specific challenges and thus requires some way of looping the carbon in the plastic – or end-of-life treatment of plastic waste.

To derive possible pathways on how to achieve carbon looping an amended WISEE model framework has been used. During the REINVENT project a plastic waste stock model has been developed, which has been used in earlier scenarios described in deliverable D4.2.

To deepen the understanding on how technologies involving circular carbon concepts could phase in into the production stock of the chemical industry, an *invest* module (called *edm-I*) for the petrochemical industry has been developed to support the calculation of scenarios co-created with experts and stakeholders during the workshops (see for the plastics sector in particular the deliverables D4.4, D4.5 and D4.9).

The new module was integrated in the existing WISEE framework. Figure 13 shows the WISEE framework and its use to derive the scenarios described in the report at hand.

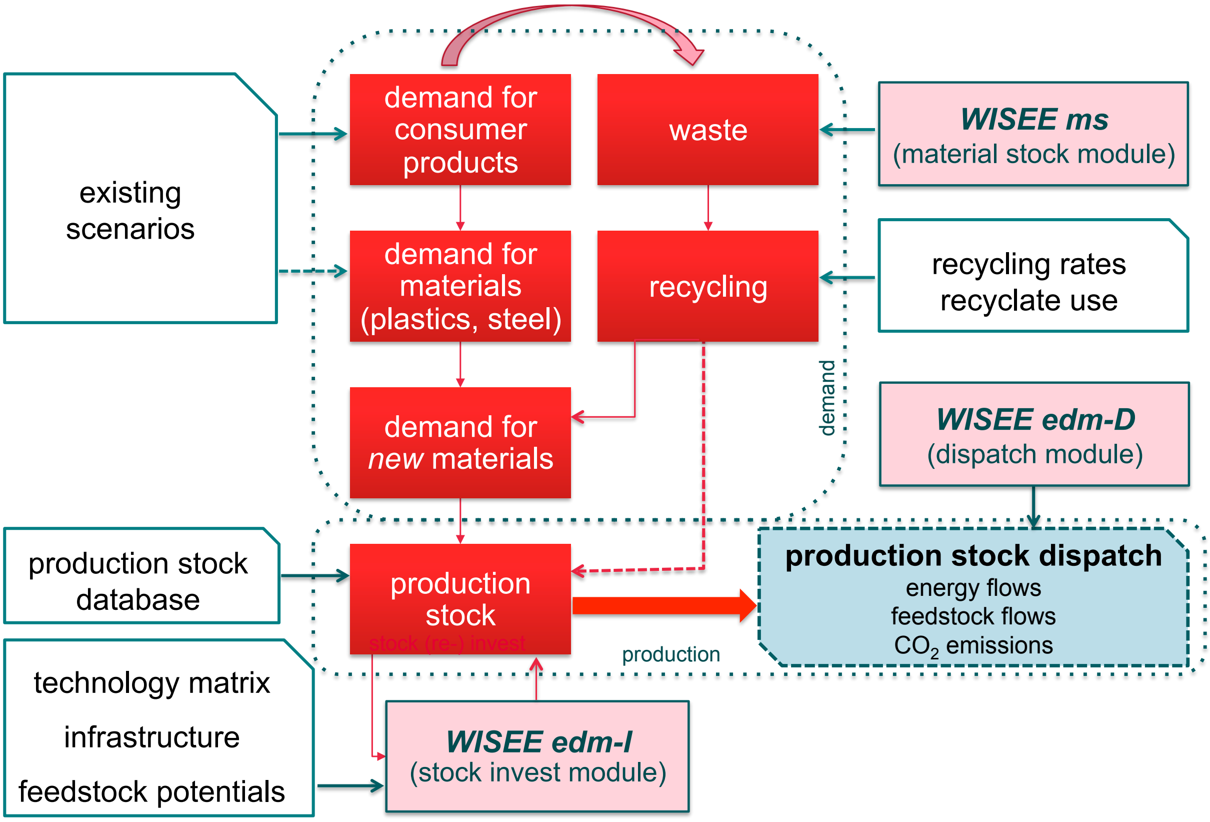


Figure 13: Modelling plastics with the WISEE model framework [source: Wuppertal Institute]

The production of plastics, with the associated demands for feedstock and energy as well as CO_2 emissions, is derived by several steps:

- Plastic demand (by plastic sorts) is derived for a BAU case by extrapolating the trend of plastic use intensity in the so- called “conversion sectors”, i.e. the economic sectors taking in

plastics and converting them into products like cars or buildings. Other demand pathways can be derived by assumptions built on top of the BAU development (i.e. savings of plastic with x% for a specific product group).
- Plastic waste "supply" is calculated by a plastic stock model. Annual plastic stock intake (previous step) and assumptions on the lifetime of the several product groups (including a distribution) drive the model.
- Assumptions on the usability of the waste for mechanical recycling as well as possible recyclates intake of the different sectors result in mechanical recycling rates and the amount of new polymers needed by matching supply and demand in each year until the end of the scenario horizon (i.e. the year 2050).
- New polymers can be produced by the production stock available in a specific scenario year. The WISEE *edm-I* module "decides" if the remaining production stock from earlier periods is sufficient or if new investment is needed to meet demand and also where in Europe such new investment could be integrated in an optimal way into the production networks. The model may also idle existing production stock (before having reached the end of technical lifetime) favouring other technologies that produce more efficiently.
- In the last step WISEE *edm-D* calculates full energy and CO_2 balances for each site considered in the EU28+2 based on the utilization rates of production stock derived by *edm-I*. *edm-D* also accounts for steam and hydrogen integration at sites (i.e. the use of steam or hydrogen by-production in other processes consuming steam or H_2).

4.1 Standard production routes for platform chemicals

The bulk of today's new polymer production (i.e. not recycled plastics) can be derived from a few so-called platform chemicals. These are:

- olefins (i.e. ethylene, propylene and butadiene),
- aromatics (benzene, toluene and xylene),
- chlorine,
- ammonia and
- methanol.

Recyclates from mechanical recycling of plastic waste are an increasing source for polymers used in the plastics converting industries. So-called chemical recycling does not play a significant role yet, but several pilot plants are operated in Europe. Chemical recycling can supply so-called monomers or platform chemicals or a synthesis gas of carbon monoxide and hydrogen.

Today's standard routes for the production of platform chemicals are described in the following in regard to energy and feedstock use as well as emissions and economic parameters like capex and opex.

Table 4: State-of-the-art production routes for platform chemicals [source: own calculations based on Ren (2009), Bazzanella/Ausfelder (2017), IEA (2009)]

process	educts	products	relevance today, EU production in [Mt/a]	feedstock (educt) use*) [t/HVC]	energy use [GJ/ t HVC]	CO_2 emissions [t CO_2/ t HVC], incl. EOL	capex [kEUR/ (t HVC *a)]
naphtha steam cracking	light naphtha	olefins, aromatics		1.3	-****)	4.3*****)	0.6
ethane steam cracking	ethane	ethylene, propylene		1.3	-****)	3.8	1.4
propane dehydrogenation	propane	propylene	0.4	1.3	-****)	3.9	0.7
FCC	heavy gas oil (HGO)	propylene (gasoline, diesel etc.)	7.2***)	5.0	0.5	3.3*****)	*not considered*
chlorine electrolysis	sodium chloride	chlorine (hydrogen)	*8.0**)*		10-12	-	
ammonia synthesis (+steam reforming of natural gas)	*(natural gas →)* hydrogen, nitrogen	ammonia	*15.2**)*		0.1	1.8******)	
methanol synthesis (+steam reforming of natural gas)	*(natural gas →)* CO, hydrogen	methanol	*1.3**)*		10	2.0	

*) "HVC" stands for *high-value chemicals* and these are defined as the target products (e.g. olefins and aromatics). By-products are indicated in the products column in brackets and are not counted as HVC.

**) Only part of the production is used for polymer production.

***) estimation.

****) included in feedstock use

*****) including emission allocations from oil refining

******) including process related emissions from hydrogen production via methane steam reforming

Another very important source of aromatics today is the catalytic reforming of heavy naphtha in refineries. As aromatics use in gasoline is very restricted by regulation, these aromatics are often used as a chemical feedstock. In the scenarios described in the report at hand catalytic reforming was not explicitly modelled.

4.2 Producer driven case

A mainly CO_2 price driven development with cross-sectoral cooperation.

The projection of the IEA's (2018) Sustainable Development Scenario in the World Energy Outlook foresees a CO_2 price of 63 \$/t in 2025 and of 140 \$/t in 2040 (equivalent to 128 €/t). To reach carbon neutrality in the model a carbon price of 200 €/t in 2040 was assumed for the PD case. For 2050 a prohibitive high price of 1000 €/t CO_2 was used as model input. It has to be stressed that such a high price is actually not needed to achieve carbon neutrality but just a technical input for the model.

Possible synergies with the fuel sector are not regarded (in line with the roadmap papers of the chemical industry)

4.2.1 Technologies and strategies

The "producer-driven" case design foresees no plastic demand reduction measures. Plastic demand develops "business-as-usual". Mechanical recycling rates and recyclates input in plastics conversion increase but demand for new plastics produced from monomers still increases as well. So a lot of new production routes have to be considered that rely on waste or biogenic feedstock – in the long run even on CO_2 from the atmosphere. These technologies all have the potential of being operated carbon neutral and are presented in the following Table 5 with their respective feedstock and energy demands as well as specific investment requirements.

Table 5: New production routes for platform chemicals [source: own compilation based on Schneider et al. (2019), Zhang/El-Halwagi (2017), Bazzanella/Ausfelder (2017), Fivga/Dimitriou (2018), Pérez-Fortes et al. (2016), Collodi (2017), dena (2017), Amirkhas (2006), Thunman et al. (2018), Thunman et al. (2019)]

process	educts	products	feedstock (educt) use [t/HVC*)]	energy use [GJ/ t HVC]	capex [kEUR/ (t HVC *a)]
plastic waste pyrolysis	sorted plastic waste	pyrolysis oil	1.6	3.5	0.5
plastic waste gasification (+MeOH synthesis)	unsorted plastic waste	(syngas →) methanol	0.4	10	0.9**)
electric steam cracking	naphtha (ethane)	olefins, aromatics	1.3 (ethane: 1.2)	9	0.6 (ethane: 1.4)
biogenic carbon processing to methanol	black liquor	methanol	3.3	19	1.1***)
DAC based methanol	CO_2, hydrogen	methanol	1.4 (CO_2) + 0.2 (H_2)	33	1.3
MtO	methanol	ethylene, propylene	2.7	0.1	0.9
MtA	methanol	para-xylene, toluene, benzene	4.3	0.1	1.1

*) “HVC” stands for *high-value chemicals* and these are defined as the target products (e.g. olefins and aromatics). By-products are indicated in the products column in brackets and are not counted as HVC.
**) excluding capex for H_2O electrolysis
***) including capex for H_2O electrolysis

4.2.2 Demand for plastics

The demand for plastics in the PD case is driven by the demand of plastic converters in the EU-28+2 (EU plus Norway and Switzerland). The sectors that have been identified as most relevant are food industry, automotive, construction sector as well as electrical equipment and electronics.

In this producer driven case plastics *demand* follows a business-as-usual pathway. In order to derive a future development, the historical trends of plastic intensity (relationship between plastic demand of this sector in tons and real gross value added of the sector) have been extrapolated to the future. GVA development has been taken from the PRIMES scenarios and sector GVA change rates for Norway and Switzerland were assumed to be the same as for the EU28.

Table 6: GVA development in the key plastic converting sectors in the EU28 in Bn€$_{2005}$ [based on Capros et al. (2016)]

	2015	2030	2040	2050
Manufacture of food products; beverages and tobacco products	249	289	326	363
Construction	593	721	810	901
Manufacture of motor vehicles, trailers and semi-trailers	270	351	398	452
Manufacture of electrical equipment	89	119	135	153
Manufacture of textiles, wearing apparel, leather and related products	59	47	41	37
Manufacture of furniture; other manufacturing	77	92	101	110

The structure of polymer demand within the sectors was assumed to be stable, i.e. the modelling cannot account for possible substitution effects between different polymers in the future. Nevertheless the projection of demand for the several polymers differs because of differing structure of demand and differing plastic demand developments between the sectors.

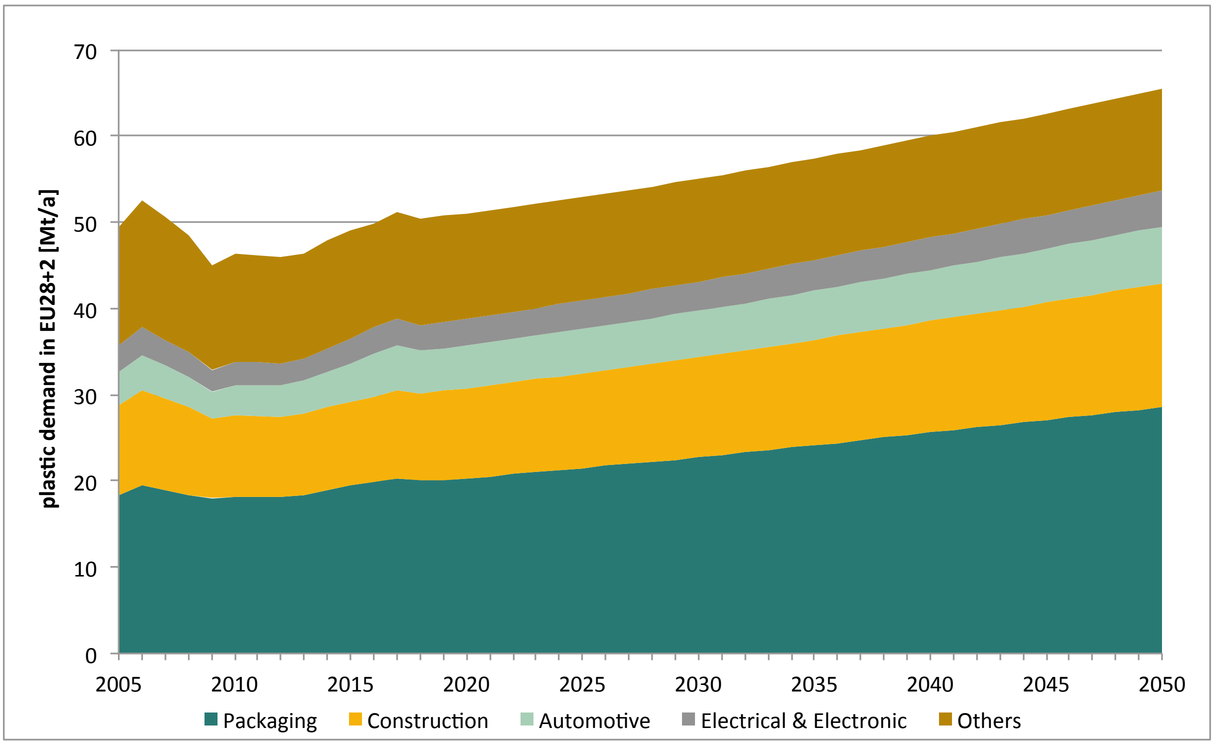
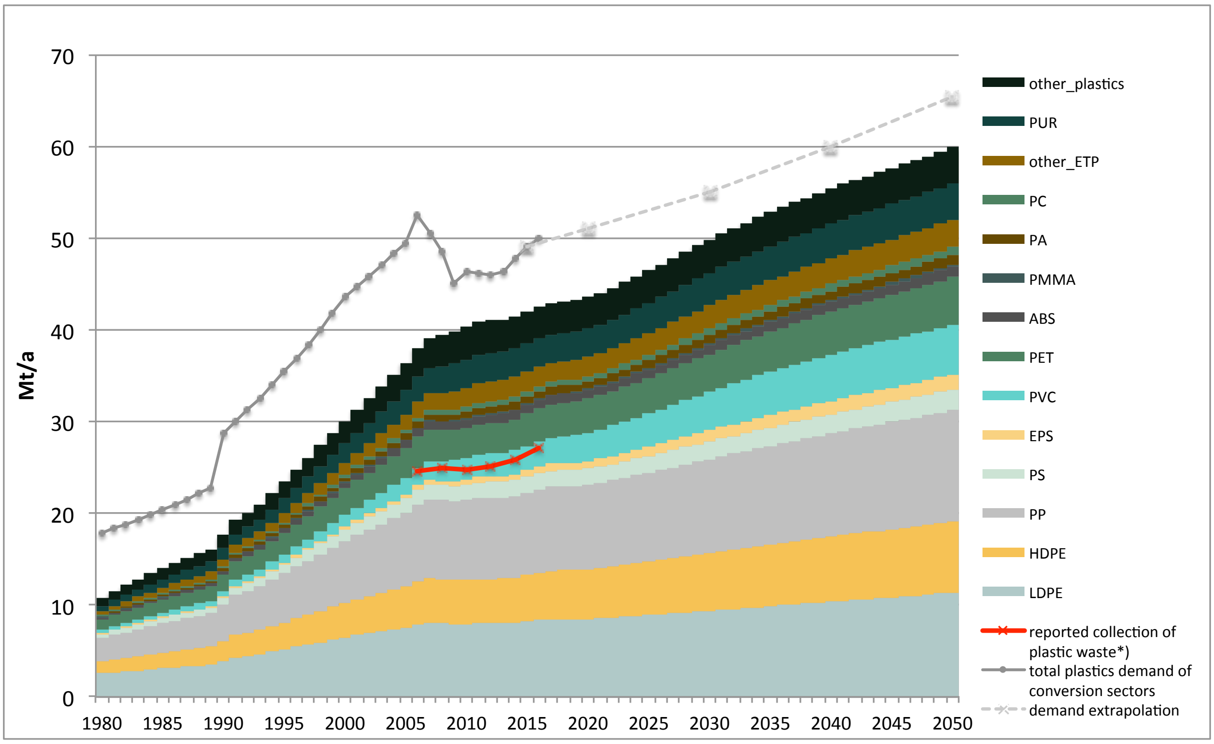


Figure 14: Development of plastics demand in the key plastic converting sectors in the “producer driven” case [source: on calculation]

Another issue changing demand structure for polymers in the future are the different recycling rates and the different potentials of the conversions sectors to use recyclates from mechanical recycling.

4.2.3 Modelling of future production networks

The available waste flows in Europe over time derived by the WISEE Plastic Stock model is shown in Figure 15.



*) The stacked surfaces show calculated waste amount resulting from the conversion of plastics within Europe. These calculated flows do not correspond to reported waste amounts in the statistics (see the red line). Products converted in Europe 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 15: Projected waste streams connected to plastic products supplied by European plastic converters in the producer driven case [source: project analysis, derived by the use of the WISEE Plastic Stock model]

The stacked surfaces in the diagram indicate overall waste flows whereas the grey line above shows the actual demand of the plastic converters in the respective year. As the grey graph lies always above the total waste stream it can be seen that the still growing demand for plastics in this business-as-usual demand case cannot be covered by waste, be it by mechanical recycling or chemical recycling – not even in the (theoretical) case where all waste could be recycled. The growing plastics stock requires a permanent inflow of additional hydrocarbon feedstock, losses in the system (exports of waste, thermal treatment) add up additional demand for new feedstock.

However, the major parts of the waste streams indicated are available for mechanical or chemical recycling in this case.

Due to energy efficiency reasons mechanical recycling was prioritized, so the difference between total waste flow and input in mechanical recycling is in principal available for chemical recycling. Actual availability is further reduced by the fact that some waste streams require deposition; in 2050 it was assumed that this flow makes up to only 400,000 tons per year.

The actual use of waste as a feedstock for chemical recycling was assessed by the *WISEE edm-I* invest model that compared cost efficiency of two chemical recycling routes with conventional fossil based routes.

The hydrogen price assumed for the late 2030s (1.44 €/kg in 2040) and the 2040s (1.23 €/kg in 2050) is an optimistic assessment representing the lower edge of a plausible range from 1.65 to 1.80 €/kg in 2030 and 1.23 to 1.34 €/kg in the 2040s and 2050s. In this case methanol could be available at

ARA[1] or Mediterranean ports at 489 €/t (2040) and 457 € in 2050 (including shipping costs of 12€/t). However, under worse conditions hydrogen supply costs could be at the higher end of the range. Higher hydrogen costs would however change the modelling results not much. "Back-stop technologies" are needed in this high plastics demand scenario and they all have similar specific hydrogen requirements.[2]

An additional important assumption is that fossil feedstock will be available at prices comparable to today in the future. Although the deep decarbonisation scenarios of the IEA (2018) show a drop in crude oil prices compared to today due to rather stable global transport fuel demand, the supply costs for shale gas based ethane and propane could be higher in the future than today. These are today's fossil benchmark feedstock for olefin investments (ethane crackers and propane dehydrogenation) and the demand for it could grow considerably mainly due to growing global demand for plastics (especially in Asia and Africa).

If ethane and propane prices grew considerably this could (together with lower hydrogen supply cost) result in higher and earlier investments in waste based and DAC based production routes in Europe.

The two chemical recycling routes are the pyrolysis of plastic waste with a pyrolysis oil as a feedstock than can be converted in steam crackers to platform chemicals and on the other hand gasification of plastic waste to produce a syngas than can be converted to methanol. Methanol can be further processed via the MTO process to olefins and via MTA process to aromatics (see above). The first route requires cleaner waste whereas the latter one may also cope with contaminated waste. It was assumed that 50% of future plastic waste is available for the first route, which is cheaper and can easier be phased in into existing production systems, with steam crackers being already available.

The assumption of high CO_2 prices in this case result in high exploitation rates for waste as a plastic feedstock over time.

Especially inland sites require new feedstock. As the refineries phase out (in the model according to age and technical lifetime of the atmospheric distillation units), these sites lose their naphtha supply and need a new feedstock. Ethane or propane is only available to low cost at coastal sites, so these sites start to import olefins (especially ethylene via pipeline) or build up chemical recycling plants as soon as the CO_2 price burden on fossil feedstock (incl. end-of-life emissions) is high enough to meet the threshold.

The plastic waste pyrolysis route is already economically viable in 2030, so already 10 million tons of plastic waste are treated in this route, which represents 100% of the assumed potential. The very early adopters are the sites with existing flexible steam crackers like Grangemouth (UK), Gonfreville (France) or Terneuzen (Netherlands).

In 2030 the big inland chemical parks in Geleen (Netherlands) and North Cologne (Cologne/Dormagen, Germany) as well as Brindisi (Italy) adept their steam cracker capacities to flexible feedstock supply and build up pyrolysis plants.

The phasing-in of methanol-to-olefins starts around 2040: By that time methanol as by-product from pulping as well as from sweet renewable electricity spots (DAC based) is available.

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[1] ARA stands for the three North Sea ports of Amsterdam, Rotterdam and Antwerp.

[2] Very high hydrogen import prices and relative low EU electricity and hydrogen prices could increase the share of electric cracking with a carbon recycling of the by-products resulting in lower methanol or green naphtha imports.

The phasing out of refinery propylene production from FCC results in a shortage of this olefin. Today, one propane dehydrogenation plant is running at Tarragona (Spain) and three other ones are under construction. Around 2030 other projects follow and fill the propylene gap until 2040. But due to being captive to a fossil feedstock these plants are not operated any more after 2040.

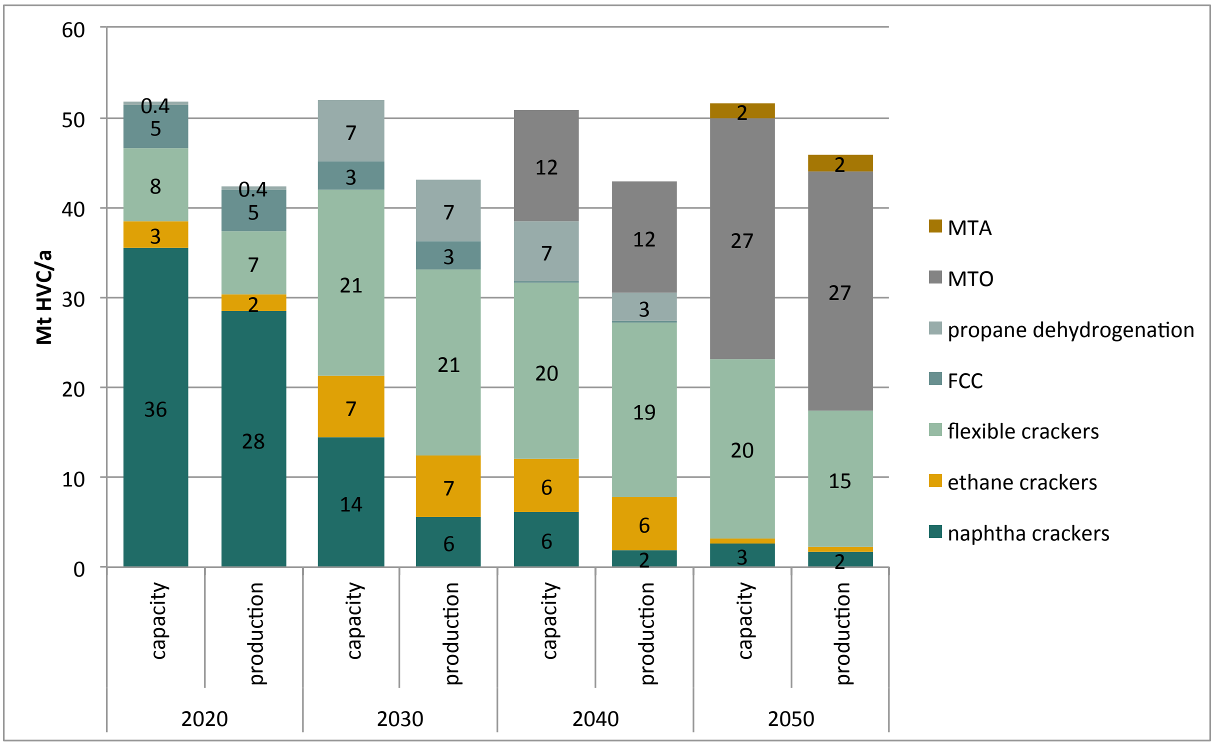


Figure 16: HVC capacities and production in the PD case [source: own calculations]

Figure 16 shows that naphtha steam crackers are being idled to a great extent already in 2030; only half of the capacity is utilized due to relatively high feedstock costs.

Waste not applicable in pyrolysis plants due to contaminations or very mixed fractions is treated in gasification plants to produce methanol. Such complex production requires several additional process steps including the subsequent processing of methanol-to-olefins or methanol-to-aromatics step. They are invested at a later stage (in 2040) with a higher CO_2 price.

It should be taken in mind that the production pathways, which were included in the technology matrix of the model represent only a fraction of possible technologies. Other technologies might offer better economic suitably to the demand structure showed in this scenario or perform better in regard to energy efficiency. So the mix of technologies pathways in regard to the general classes (e.g. steam cracking vs. MTO) might be different if other technology types would have been considered. The technology pathways taken can however be understood as to be prototypical for a bunch of technologies and the mix derived by the model is not only consistent in regard to the assumptions taken but also realistic at least in qualitative terms.

The following map shows the production of platform chemicals in Europe in 2050.

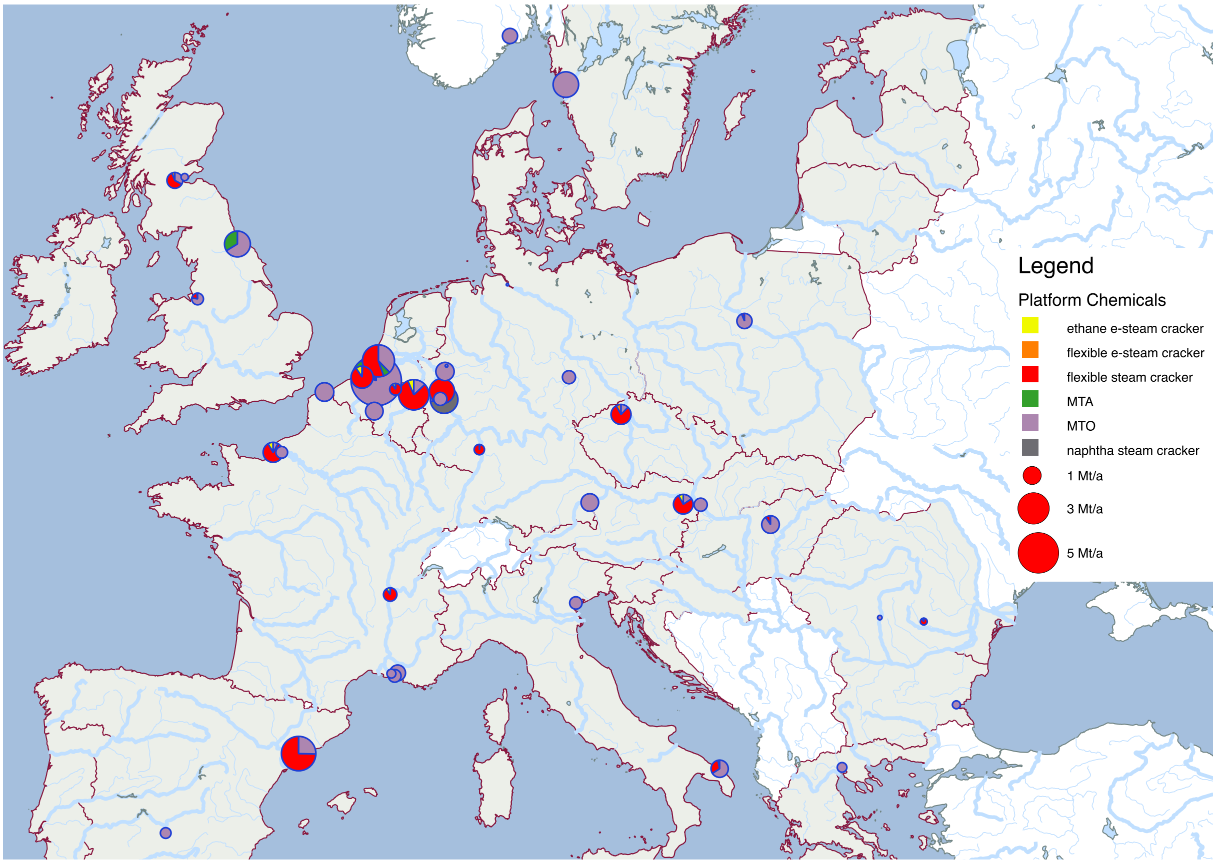


Figure 17: Map on HVC production in 2050 in the PD case [source: own calculation and illustration]

In the PD (i.e. high-production level) case today's chemical clusters are still there. The concentration of cracking facilities in Western Europe around the ARA ports is striking. This is mainly due to the complex value chains there, which depend on various platform products (including aromatics). Cracking offers synergistic production in this case. Other sites depending on ethylene and propylene only make use of the emerging availability of methanol as renewable feedstock and rely on MTO plants.

The full energy balance for the plastics sector in the EU28+2 is shown in the following Figure 18. It includes nearly all primary energy use including the feedstock. Delta between energy use and the energy content of the products is the conversion loss. Today, this loss accounts to around 40%. In the future, with more sophisticated procedures it could easily reach 50%. It has to be stressed that the system boundary here does neither include today's losses in refineries when supplying naphtha nor methanol production in the future. If they are taken into account as well losses are even higher.

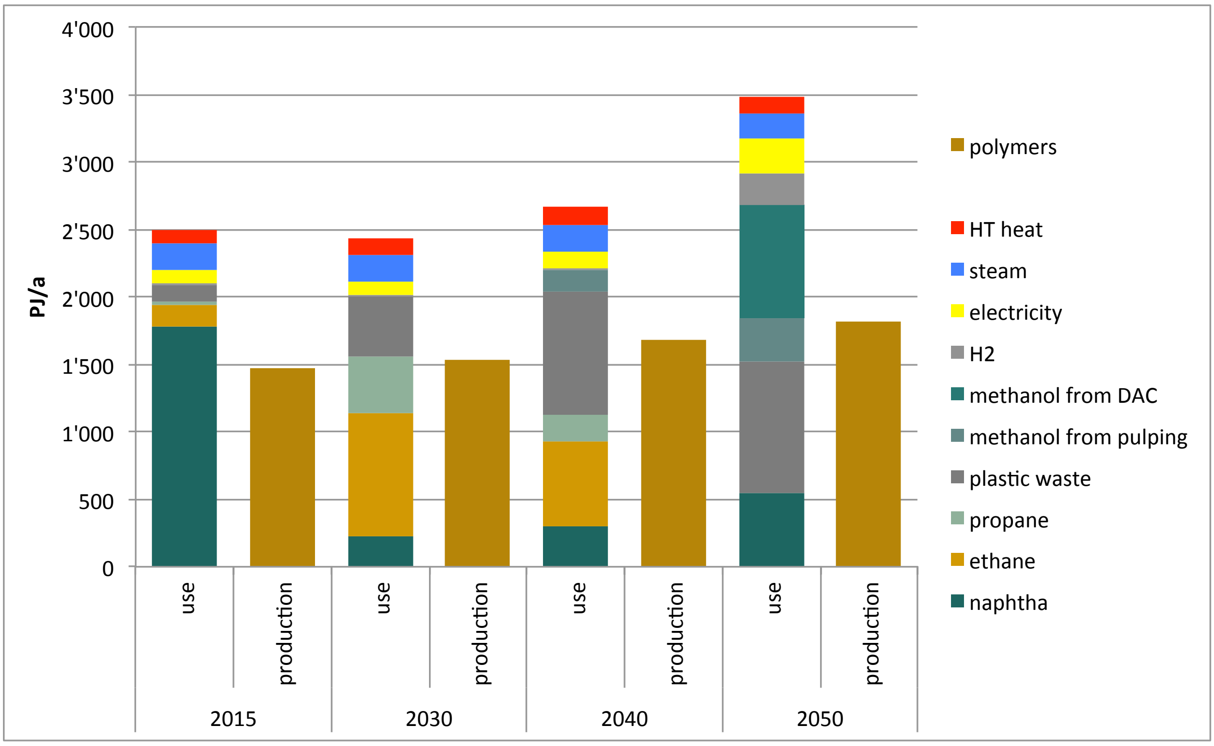


Figure 18: Energy balance for plastics production in the EU28+2 (including feedstock use) in the PD case [source: own calculation]

Finally, the CO_2 balance for the whole plastic sector is displayed in Figure 19. It includes end-of-life (EOL) emissions of the plastics in case if it is produced from fossil feedstock. Plastics from waste are considered as not having a CO_2 burden, as these EOL emissions are allocated to an earlier year of fossil feedstock extraction and refining. Biomass use as a feedstock is consequently not considered as having negative emissions but being CO_2 neutral. Emission factors used to calculate emissions related to energy use in the manufacturing process are documented in Annex 1.

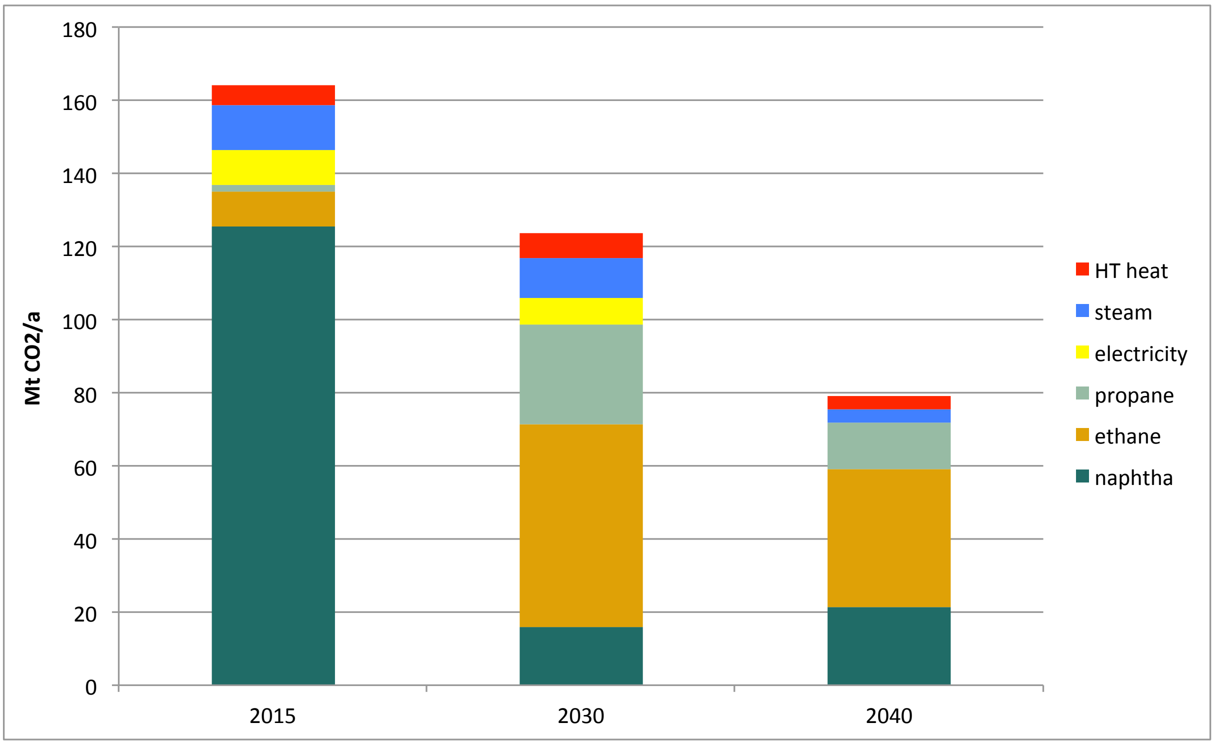


Figure 19: CO_2 emissions related to plastics production in the EU28+2 in the PD case [source: own calculations]

CO_2 cuts in 2030 are around 26% compared to 2015 and decrease much faster afterwards. 57% are achieved in 2040. Higher cuts would be possible if green naphtha would be imported instead of fossil. In 2040, with a CO_2 price of 200 €/t, it is available at a price of 1900 €/t, which is not competitive yet to the import of fossil naphtha. In 2050 renewable naphtha is available at a price of 1400 €/t and all remaining naphtha import is then from renewable sources. As all other feedstock is either from waste or from renewable sources a well the system will then be CO_2 neutral.

4.3 Plastics in a Circular Economy

4.3.1 Technologies and strategies

Technologies used to produce plastics are the same as in the “producer driven” case and are documented above in section 4.2.1.

However, the CE case involves important plastic demand management measures that apply to steel consuming and plastic consuming goods like cars and buildings as discussed above in section 3.2.2. For plastics an additional reduction of use in packaging was assumed (see below).

4.3.2 Demand for plastics

The “Circular Economy” case includes assumptions on a considerable reduction of plastic use. For the automotive and the construction sector these assumptions were taken in analogy to the case described for steel in section 3.2.2.

In addition, for packing an additional reduction of 50% compared to the baseline was assumed. In such a case 2050‘s plastics demand for packaging would be at the level of 1997 or 70% of that in 2017.

Such a reduction will only be feasible if logistics, regional value chains and consumer behaviour change considerably. Figure 20: Development of plastics demand in the key plastic converting sectors in the "Circular Economy" case [source: on calculation]

shows the respective development over time.

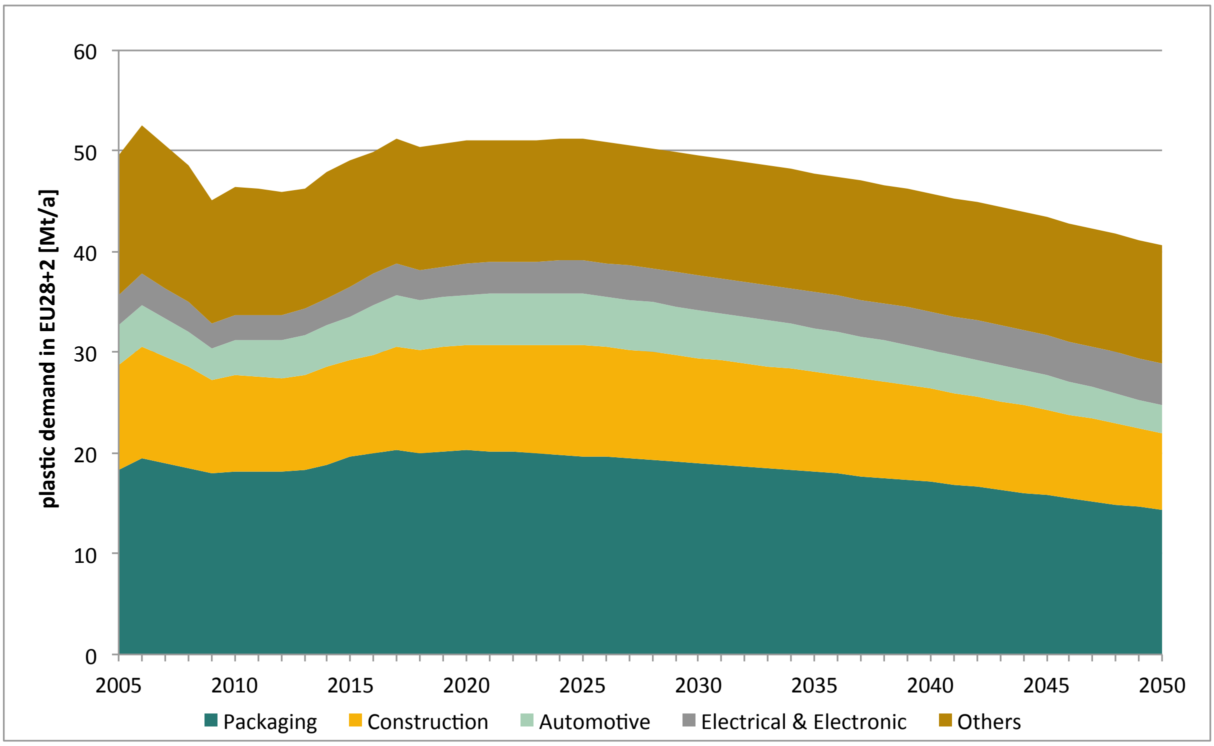


Figure 20: Development of plastics demand in the key plastic converting sectors in the "Circular Economy" case [source: on calculation]

The following Figure 21 shows the sectoral plastic use today, 2030 and 2050 differentiating between recyclates use (according to technical potentials) and new plastics produced from monomers. We assume that recyclates use is increased considerably compared to today reaching levels of up to 20%.

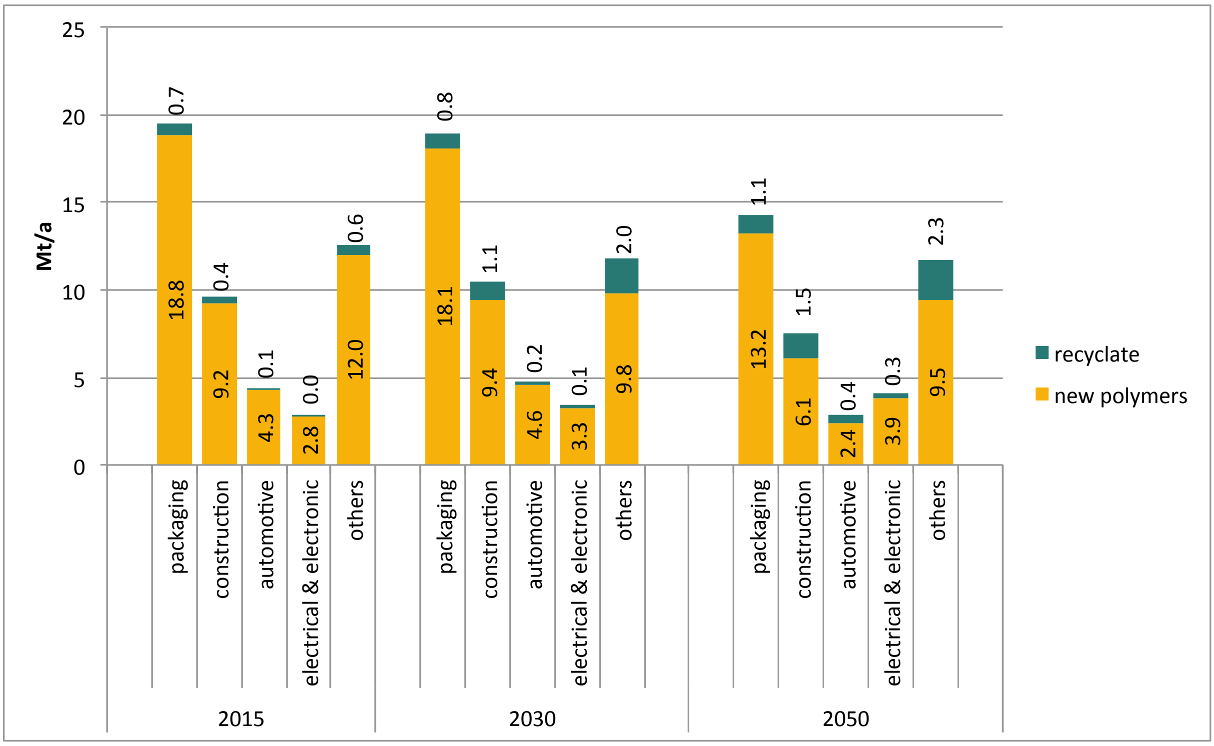
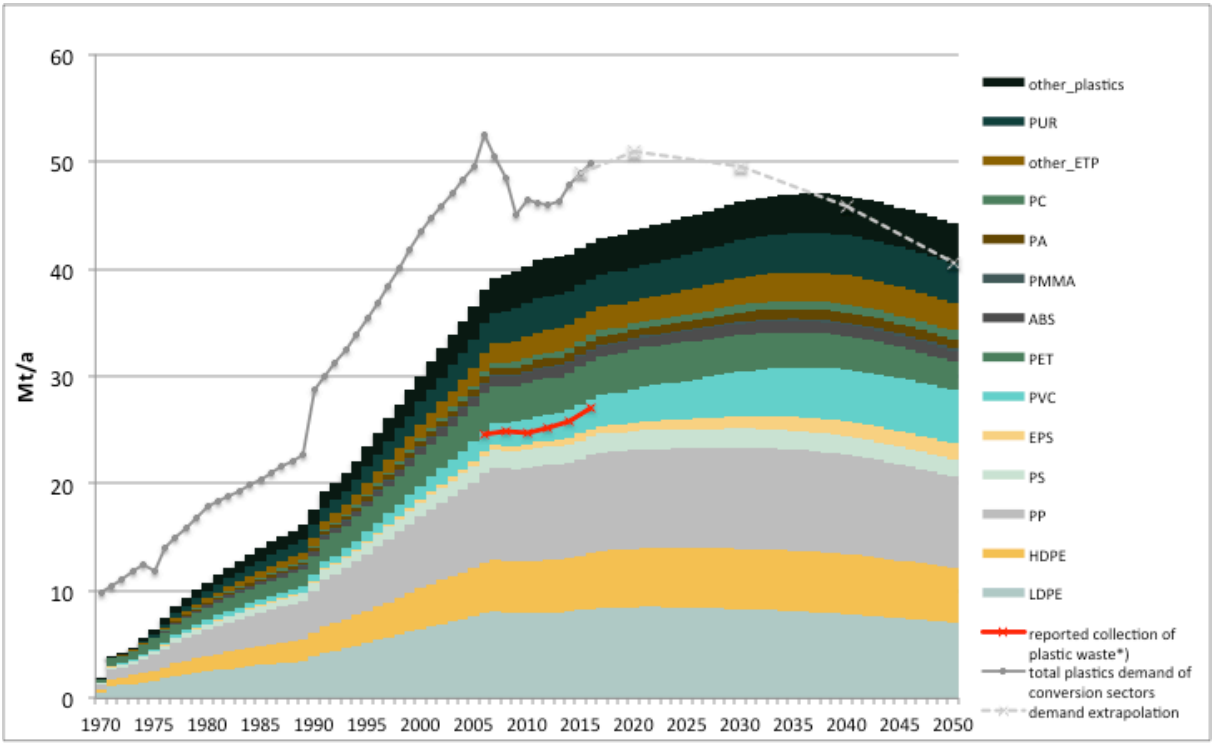


Figure 21: Plastics use in the key plastic converting sectors in selected scenario years [source: own calculations]

4.3.3 Modelling of future production networks

The CE case shows a completely different development of plastics demand. With the rapid decrease after 2020 (theoretically) available waste amounts even exceed demand after 2035. Due to losses, low qualities and exports there will be however still a need for primary production in this case.



*) see footnote in Figure 15

Figure 22: Projected waste streams connected to plastic products supplied by European plastic converters in the Circular Economy case [source: project analysis, derived by the use of the WISEE Plastic Stock model]

The following Figure 23 shows the technology mix for the supply of platform chemicals in the CE case. Decrease in capacity and production is due to lower demand and also to higher recyclates use (see above). Like in the PD case, many crackers are rebuilt in the 2020s and 2030s as flexible crackers. Thus, they can take up ethane in the mid-term but also run on pyrolysis oil from plastic waste in the long run.

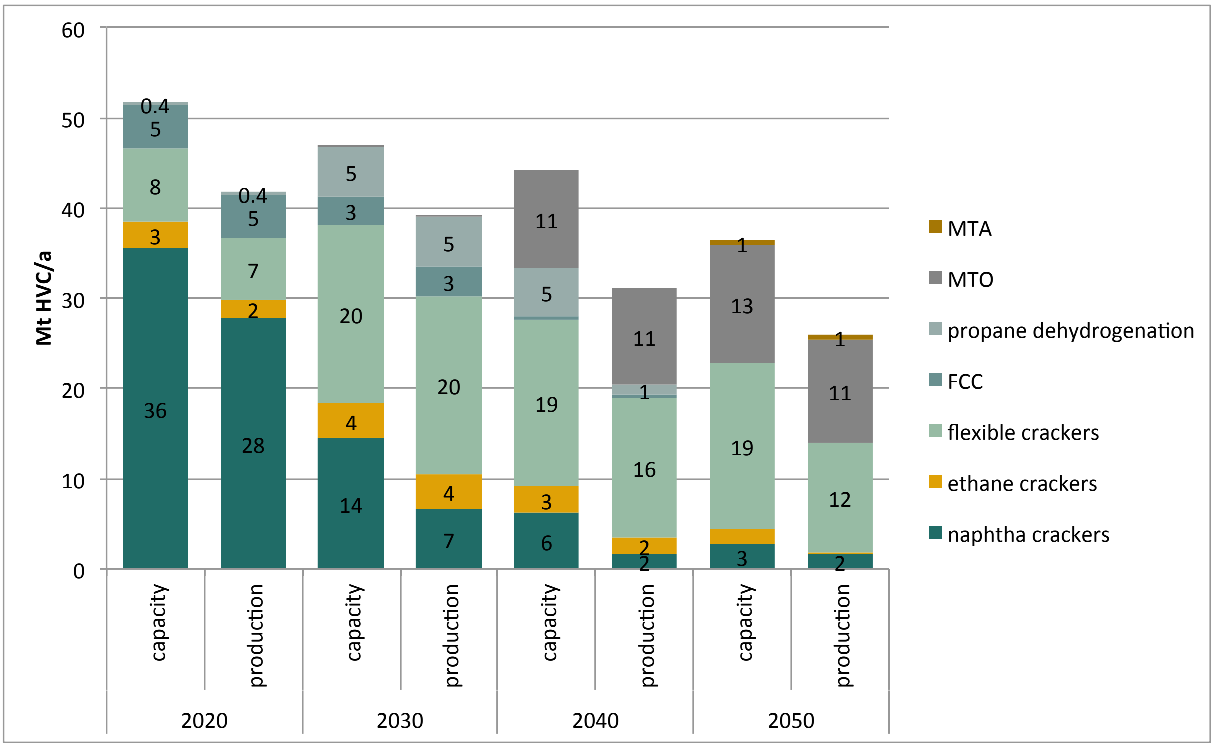


Figure 23: HVC capacities and production in the CE case [source: own calculations]

Taking also Figure 24 into account we see that methanol from pulping comes in in 2040 and plastic waste gasification is then an additional source used to produce methanol (the latter not showed in the figures). Respective methanol processing capacities are built-up as well (Figure 23). The CE case does without the two most expensive options to supply feedstock, which are DAC based methanol import and methanol based on by-products from electrified steam crackers. However, naphtha imports are still necessary in 2050 especially for butadiene supply by naphtha based steam cracking.

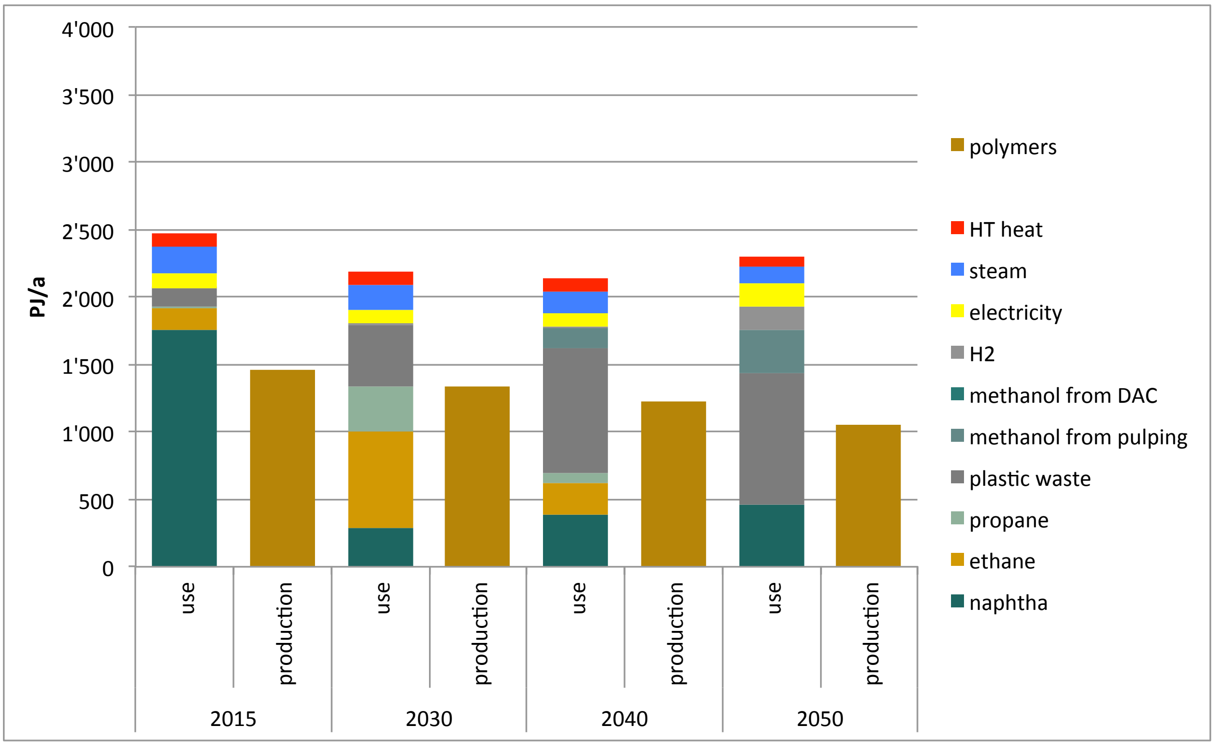


Figure 24: Energy balance for plastics production in the EU28+2 (including feedstock use) in the CE case [source: own calculation]

CO_2 emissions are illustrated in Figure 25, showing a steeper decline than in the PD case by 32% from 2030 to 2015 and by almost 70% until 2040.

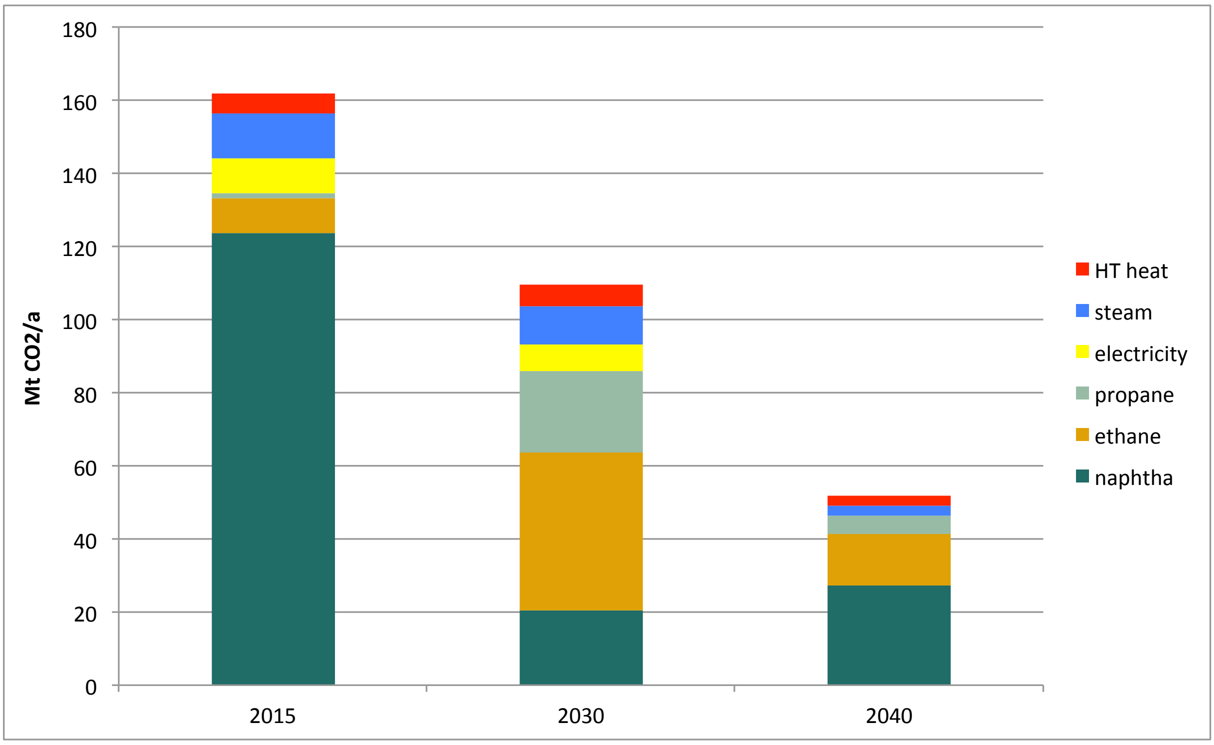


Figure 25: CO_2 emissions related to plastics production in the EU28+2 in the CE case [source: own calculations]

Finally, Figure 26 shows the map of remaining production facilities to produce platform chemicals in the EU in 2050. In the CE cases with shrinking demand for plastics only the most efficient clusters survive. The Petrochemical triangle of Flanders, South Holland and Rhine-Ruhr – today having a 50% in production capacities – improves its market share. Many other production sites (like e.g. Ludwigshafen) are mothballed or scaled down.

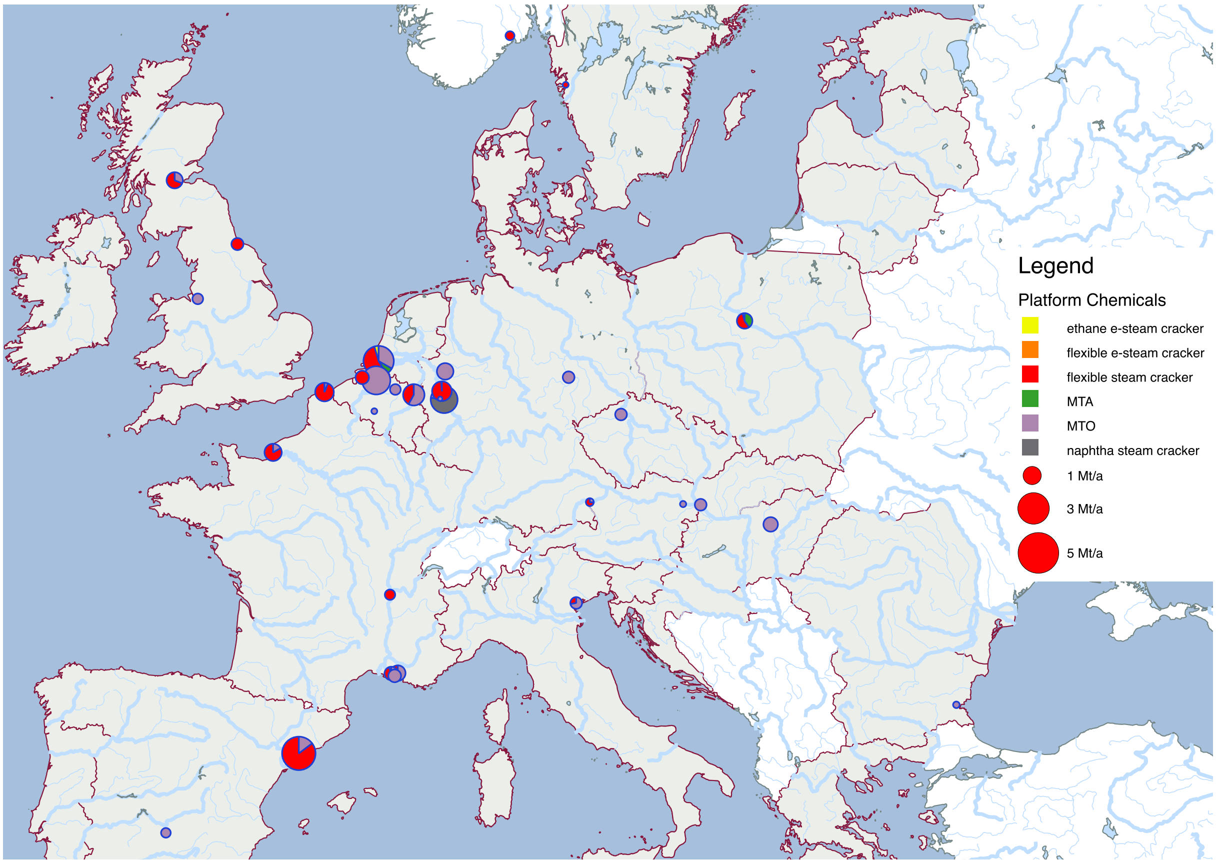


Figure 26: Map on HVC production in 2050 in the CE case [source: own calculation and illustration]

5 Pulp and Paper

Demand development pathways for paper and pulp in the EU-28 have been taken from the prior works by PBL in WP 4.2 and are described in deliverable D4.2. There is thus no extra section on demand development in this chapter. Possible substitution between the plastics and the paper sectors has not been taken into account. Admittedly, significant effects are to be expected especially in a case with massive plastics reduction in the packaging sector as described in section 4.3.2. The estimation of substitution effects between the sectors was however not part of the core works in REINVENT.

5.1 Pulp and Paper in a Carbon Looping Economy

5.1.1 Technologies and strategies

The core strategy pursued in the “carbon looping” (CL) case is the strictly utilization of biogenic carbon in the pulping industry for material use. The hydrocarbon by-product of the dominating pulping process (sulphate process) is black liquor, which is in most cases used as a fuel in the local CHP plants of the pulp industry. Energy content of black liquor is high enough to supply steam and electricity required for the pulping process and often also for the subsequent step in the value chain of paper production – in case of integrated production. Many plants have however excess energy available, which is supplied to district heating grids.

In a carbon looping economy the steam supply could be electrified using renewable electricity, e.g. from wind or water paper power. High potentials of these energy sources are available in Sweden and Finland, which are the major pulp producing countries within the European Union. The challenge is here to build up the new electricity production capacities as well as to strengthen the electricity grids to offer exchange between the different regions within the countries as well as with Western Europe. Transport grid is weak in the two countries and interchange of electricity would be necessary to ensure continuous supply of renewable electricity, which is a prerequisite for a thorough electrification strategy.

CHP would in such a case not be needed any more (but could still be used as a local backup) and black liquor would not be needed any more as a fuel in the pulping process. The hydrocarbons in this fuel could thus be used in other sectors. The standard technology to utilize them is black liquor gasification (BLG). This technology has been studied in detail for more than a decade in several R&D projects and provides a syngas of CO, hydrogen and CO_2 which can be used to produce any hydrocarbon fuel (like diesel or DME) for the transport sector or to produce methanol and platform chemicals as described above in sections 4.2.1 and 4.3.1.

Within REINVENT we focus on the use in the chemicals sector to analyse the possible cross-sectoral synergies in de-fossilizing both sectors. An extra supply of hydrogen via water electrolysis can be combined with gasification to provide an optimal stoichiometry in order to use all available CO and CO_2 in the syngas. In such a combination methanol output can be increased by a factor of 2.6.

The following Table 7 compares a rough energy balance of the new concept to the conventional route.

Table 7: Energy balance*) of a conventional CHP route and a Carbon Looping concept in the sulphate pulping process [source: own calculation based on Suhr et al. (2015), Larson et al. (2006a)]

	unit	conventional CHP concept	carbon looping concept
electricity demand of pulping	GJ/t pulp	2.2	2.2
electricity demand of BLG	GJ/t pulp	0	1.8
electricity demand of electrode boilers	GJ/t pulp	0	9.3
electricity demand of H_2O electrolysis	GJ/t pulp	0	7.8
electricity demand of MeOH synthesis	GJ/t pulp	0	0.3
electricity supply by CHP	GJ/t pulp	-6.2	0
steam demand of pulping	GJ/t pulp	11.6	11.6
steam demand of MeOH synthesis	GJ/t pulp	0	0.4
steam supply by CHP/biomass boiler	GJ/t pulp	-11.6	-2.8
steam supply by electrode boilers	GJ/t pulp	0	-9.3
methanol supply	t MeOH/t pulp	0	-0.53

*) energy demands are given as positive values, supply as negative.

Table 8 gives an indication of the economics when introducing the new concept. The Carbon Looping concept is associated with higher pulp production costs, the delta amounts according to our rough calculation to 295 € per ton of pulp.

Table 8: Comparison of costs between a conventional CHP route and Carbon Looping [source: own calculations based on IRENA (2012), Larson et al. (2006a), Larson et al. (2006b), ECN/Lux Research (2018), Zetterholm et al. (2018), Schneider et al. (2019)]

	unit	conventional CHP concept	carbon looping concept
capex CHP	EUR/t pulp	88	-
capex biomass boiler	EUR/t pulp	-	11
capex electrode boiler	EUR/t pulp	-	6
capex gasification	EUR/t pulp	-	24
capex MeOH synthesis	EUR/t pulp	-	12
capex H_2O electrolysis	EUR/t pulp	-	22
electricity purchase costs	EUR/t pulp	-33	273
fixed opex	EUR/t pulp	27	29
total costs	EUR/t pulp	82	376
resulting MeOH supply costs)*	*EUR/t MeOH*	-	*561*

*) defined as differential costs to the CHP route and per tonne of methanol output (without transport costs to chemical sites)

The cost differential between carbon looping and the standard route of using the BL in a CHP can be regarded as the supply cost for the methanol, which is produced as by-product. Our calculation in Table 8 displays methanol supply costs of 561 EUR/t for 2040 and 2050, which is at still similar levels than DAC based methanol from a sweet spot like the MENA region (which could however be cheaper in the long run).

The main difference compared to a DAC-based methanol is however, that TRL levels for the BLG route are much higher today than for the DAC route. For this reason and also considering European security of supply the BLG route is preferred to the DAC route as a supply of methanol for chemicals (see sections 4.2.1 and 4.3.1). We thus assume that the conversion of black liquor treatment in the pulping process (and the parallel phase-in of electricity-based steam supply) will be driven by the chemical sector searching for a secure supply of renewable hydrocarbons.

5.1.2 Modelling of a future production networks

In the Carbon Looping case the European Union's pulp and paper industry evolves from a single product supplier to a core hydrocarbon feedstock supplier. Hydrocarbon output thus increases from 77 million tons of paper in 2015 to an aggregated output of 100 million tons in 2050 – including 14 million tons of high-value methanol for the plastics industry.

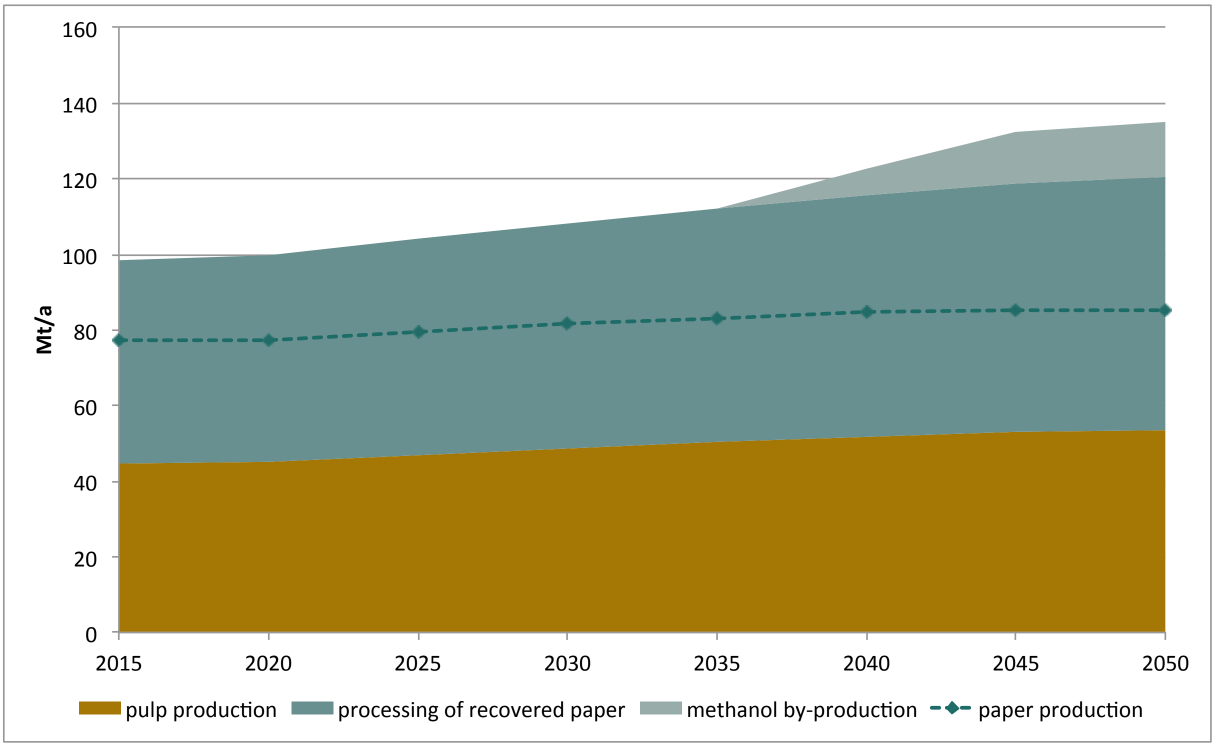


Figure 27: Fibre production in the pulp and paper industry in the CL case as well as methanol by-production [source: own calculation]

Energy use in the sector narrows down from 140 PJ/a to 100 PJ. Electricity use increases from 200 PJ to 340 PJ in 2035 and to 800 PJ by 2045. Biomass use as an energy carrier is restricted to bark use in the pulping mills and some waste paper use in non-integrated paper mills. It thus shrinks from today's level of 770 PJ to an annual use of 220 PJ in 2050. Other energy carriers like oil, gas and coal are completely phased-out.

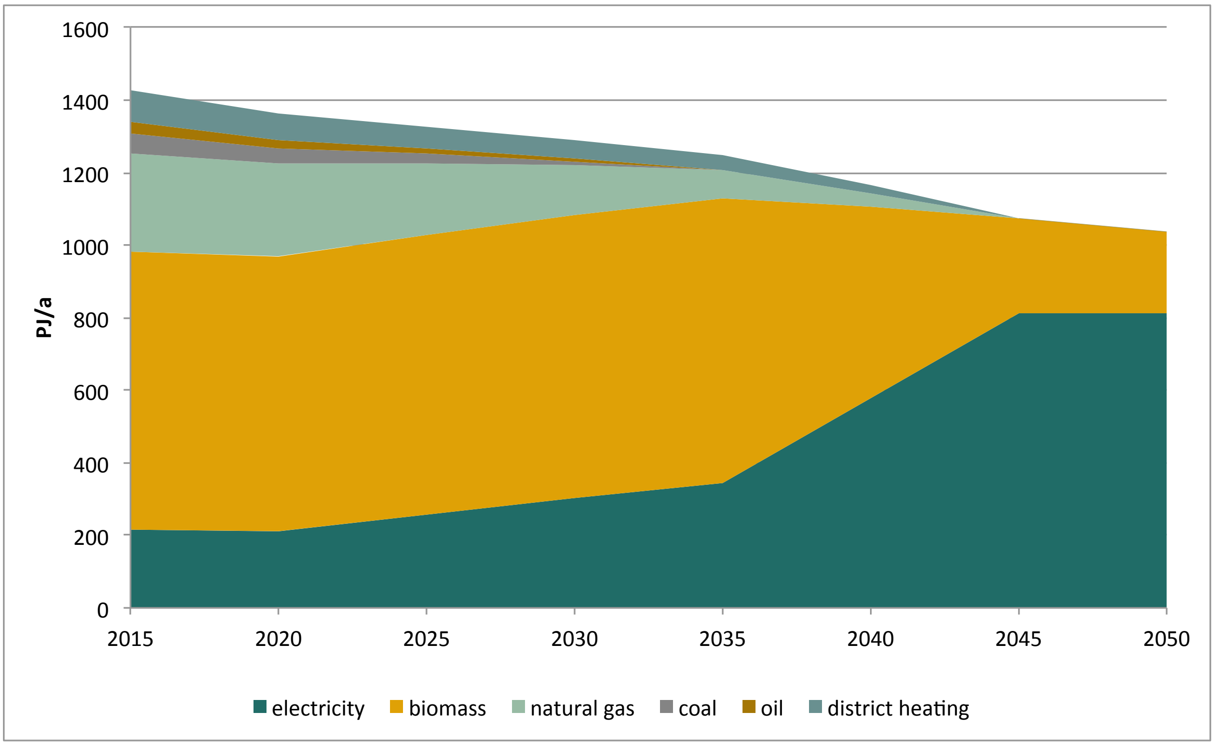
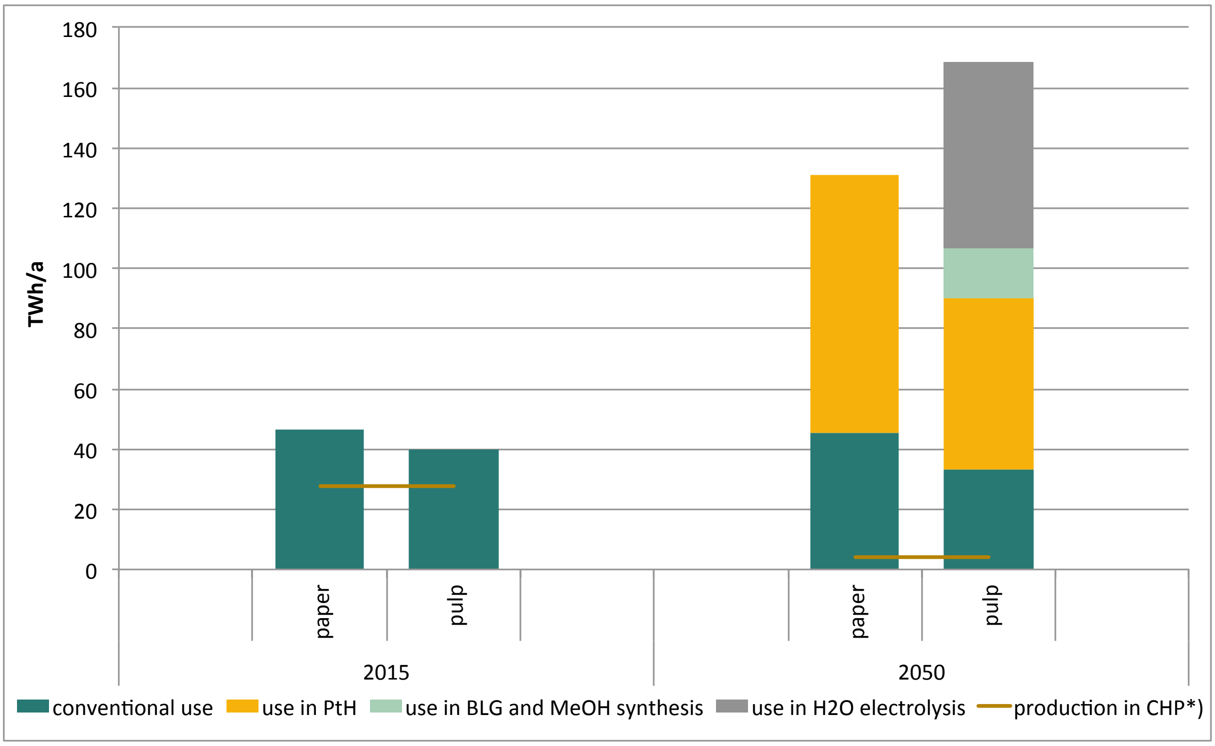


Figure 28: Primary energy use in the pulp & paper sector in the CL case (energy content of products excluded) [source: own calculations]

Electricity and/or hydrogen use for methanol production is not included in Figure 28 as these energy requirements are due to methanol by-production and not to fibre production. However, the respective demands will occur at sites of the pulping industry and are thus relevant for the sector as well.

Figure 29 displays the respective demands and also differentiates other electricity use between use for pulp and for paper production. This is relevant in regard to effects on regional electricity systems – especially for the Nordic countries, where pulp industry is concentrated. Both at pulp and paper mills electricity use will in a CL case increase by more than 100%, but at the pulping sites electricity use will increase even more due to new electricity consumption for black liquor to methanol processing (incl. hydrogen supply by H_2O electrolysis).



*) CHP electricity production is indicated for each year at an aggregate level for both installations at pulp and paper manufacturing sites.

Figure 29: Electricity balance of the pulp and paper sector in the CL case [source: own calculations]

5.2 CCS driven case

The pulp and paper industry in the EU-28 emits 74 million tons of CO_2 annually, of which 44 Mt are of biogenic origin and mostly result from pulping. Whereas paper making form recycled paper in a CCS driven case will still go for (direct or indirect) electrification of steam supply the pulping process with its massive biogenic fuel by-production (bark and black liquor) has been identified as a possible field for BECCS application. Most European pulping sites are located in Sweden and Finland and many of them are located at the Baltic Sea coast offering good conditions for CO_2 transport. Possible sinks for CO_2 storage are mainly depleted oil and gas fields in the North Sea. Onshore transport to Norway by pipeline or other onshore transport would be very costly, so the possible sites where BECCS could be applied were restricted to such lying at the coast and having already port facilities nearby.

Our analysis revealed 22 suitable locations displayed in Table 9. Sites with pulping facilities where identified in a first step by analysing the biogenic share of CO_2 emissions. In a second step sites in Sweden and Finland were filtered and in a third step the remaining sites where analysed in regard to the distance of their location to the coast.

The column “NACE code” refers to the main activity by the company running the site. “17.11” stands for companies making the majority of their value added by pulp production, whereas “17.12” stands for companies getting their value added mostly from paper production. The table thus also contains sites with integrated pulp and paper production.

Table 9: Identified pulping sites suitable for carbon capture [source: own analysis based on E-PRTR data by EEA]

pulping site	state	NACE code	Mt CO_2 emissions (2015)	biogenic share of CO_2
Metsä Fibre Oy Kemi	FI	17.11	1.6	96%
Metsä Fibre Oy, Rauman tehdas	FI	17.11	1.3	90%
STORA ENSO OYJ, Oulun tehdas, Oulu	FI	17.12	1.4	81%
Stora Enso Oyj, Sunilan tehdas	FI	17.11	0.9	95%
UPM KYMMENE OYJ, UPM, Pietarsaari	FI	17.11	1.9	100%
BillerudKorsnäs Karlsborgs AB	SE	17.12	0.8	99%
Bravikens Pappersbruk	SE	17.12	0.1	94%
Domsjö Fabriker AB	SE	17.11	0.5	99%
Korsnäsverken	SE	17.12	1.2	100%
Metsä Board Sverige AB, Husums fabr	SE	17.12	1.6	97%
Mondi Dynäs AB	SE	17.12	0.6	98%
SCA Munksund	SE	17.12	0.7	97%
SCA Obbola AB	SE	17.12	0.5	95%
SCA Ortviken	SE	17.12	0.3	95%
SCA Östrands massafabrik	SE	17.11	1.2	99%
Skutskärs Bruk	SE	17.11	1.8	100%
Smurfit Kappa Kraftliner Piteå	SE	17.12	1.2	99%
Södra Cell Mönsterås	SE	17.11	1.9	99%
Södra Cell Mörrum	SE	17.11	1.1	97%
Södra Cell Värö	SE	17.11	1.1	100%
STORA ENSO NYMÖLLA AB	SE	17.12	0.7	89%
Vallviks Bruk	SE	17.11	0.6	99%
total			23.0	

The analysis revealed a static potential to get 23 Mt of CO_2 annually into a BECCS system. The actual CO_2 to be stored is calculated by extrapolating CO_2 amounts according to pulp production and by assuming a 90% capture rate in a *post combustion system*.

According to own calculations CO_2 transport and storage costs could amount to 17.50 €/t CO_2.[3] Capture costs of 67 €/t for a stand-alone pulp mill and of 77 €/t for an integrated pulp and paper mill are given in the literature for a post combustion concept (IEA GHG 2017) and add up to total mitigation costs of 84.50 €/t or 94.50 €/t. These cost amounts given a phase-in from 2030 seems to be feasible reaching full implementation by 2040. In such a pathway CO_2 amounts to be stored from pulping could reach 150 Mt in 2040 and 400 Mt in 2050 (see Figure 30). If only depleted oil and gas fields are taken into account as possible sinks a storage capacity of 785 Mt could be used according to Bergmo et al (2014). So the absolute storage capacity would be sufficient, but limitations in possible injection rates could still be an issue.

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[3] The underlying parameters are an interest rate of 8%, a distance of 2’800 km from the pulp mill to the offshore storage site and a 40kt ship.

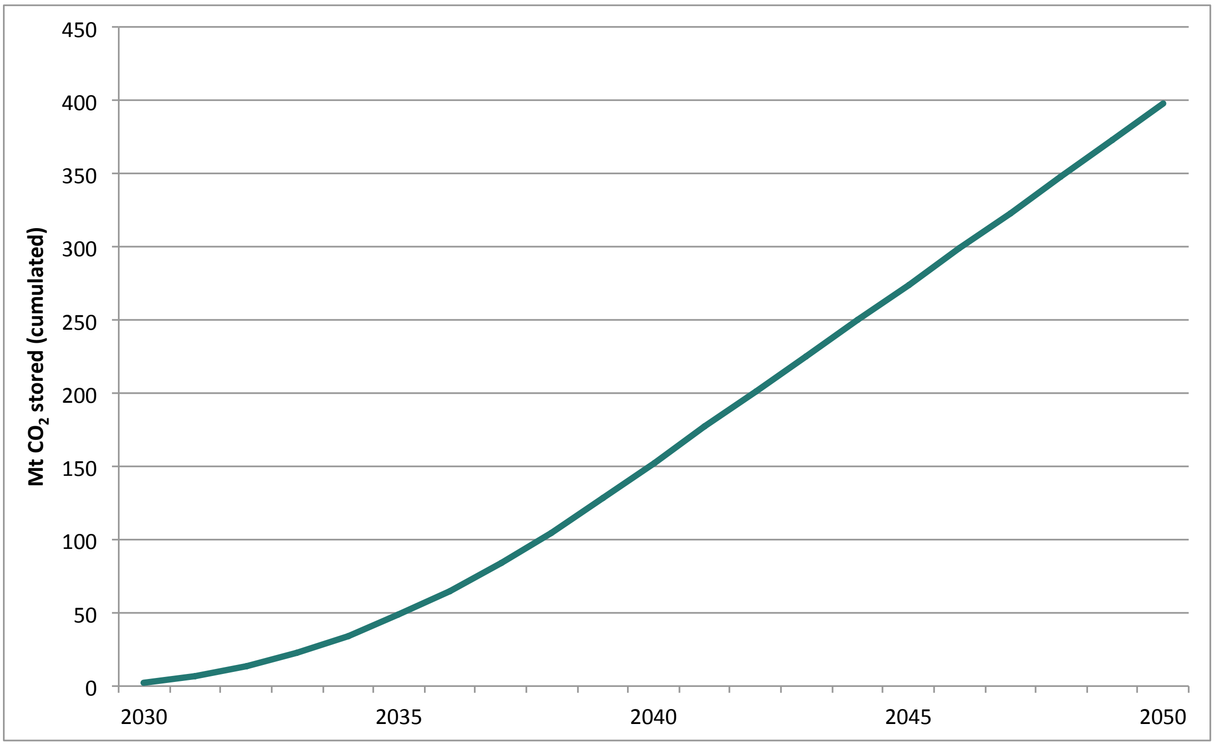


Figure 30: CO_2 stored in the BECCS case [source: own calculations]

Figure 31 indicates primary energy use in the sector showing a constant share of bioenergy and electricity taking over the role of fossil fuels.

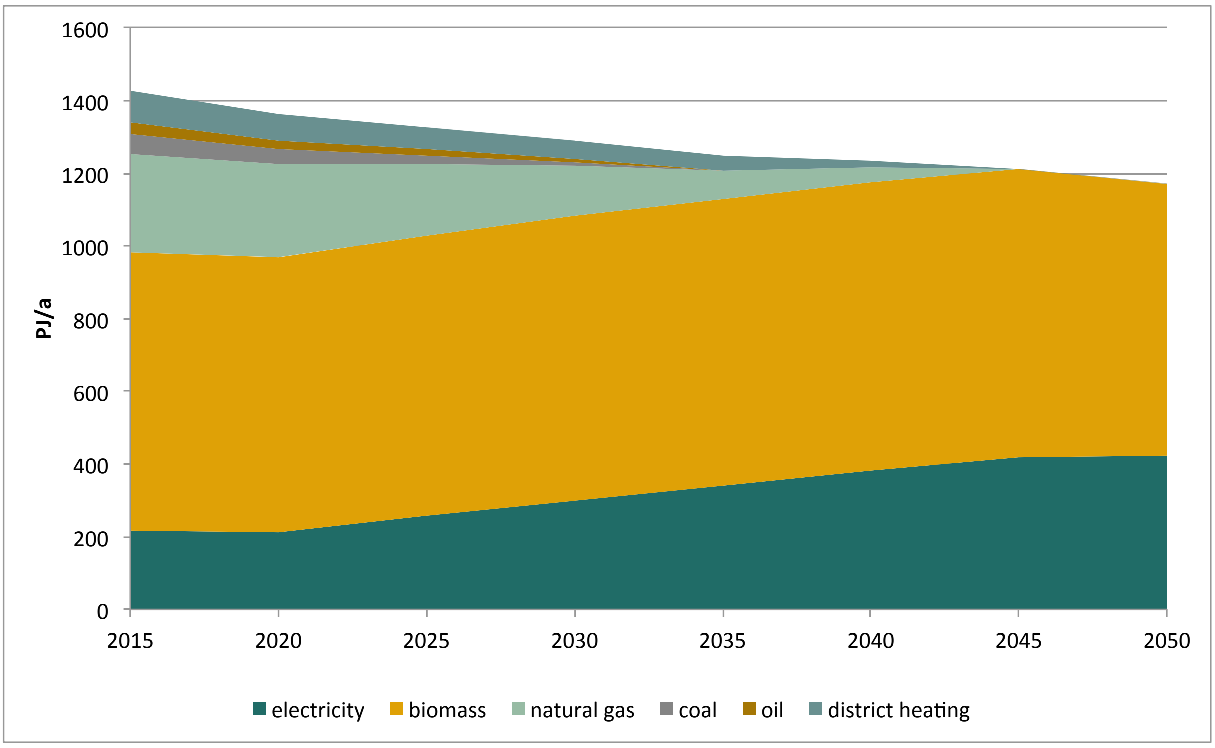
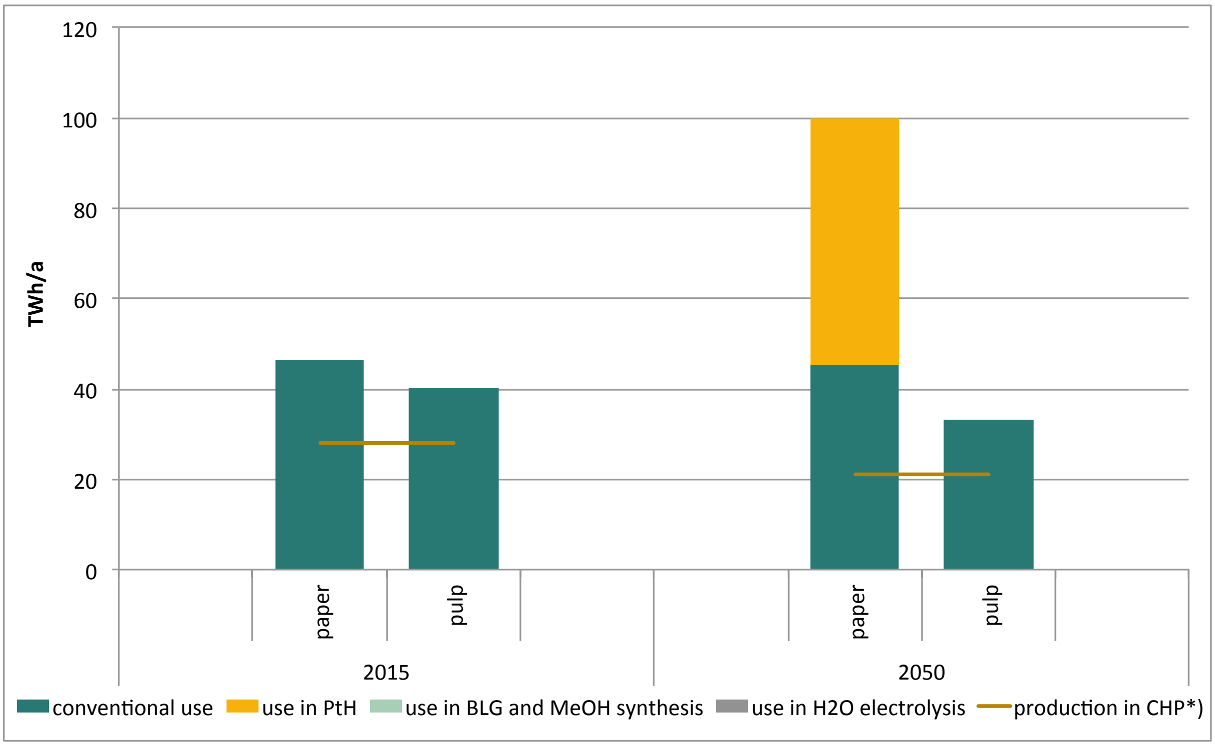


Figure 31: Primary energy use in the pulp & paper sector in the BECCS case (energy content of products excluded) [source: own calculations]

Figure 32 shows the electricity balance for the BECCS case. Paper making requires additional electricity from the grid in 2050 and CHP electricity production is lower due to phasing out of CHP at non-integrated paper mills. Annual net electricity demand of the sector reaches ca. 110 TWh in 2050.



*) CHP electricity production is indicated for each year at an aggregate level for both installations at pulp and paper manufacturing sites.

Figure 32: Electricity balance of the pulp and paper sector in the BECCS case [source: own calculations]

CO_2 emissions of the sector for both cases are displayed in Figure 33. The introduction of BECCS in the 2030s results in a deep cut of emissions reaching net zero around 2033. In the Carbon Looping case net zero emissions are reached in 2045. However, methanol by-product output means an additional credit for the sector in the CL case as it results in faster emission reductions in the plastics sector (not displayed in the figure).

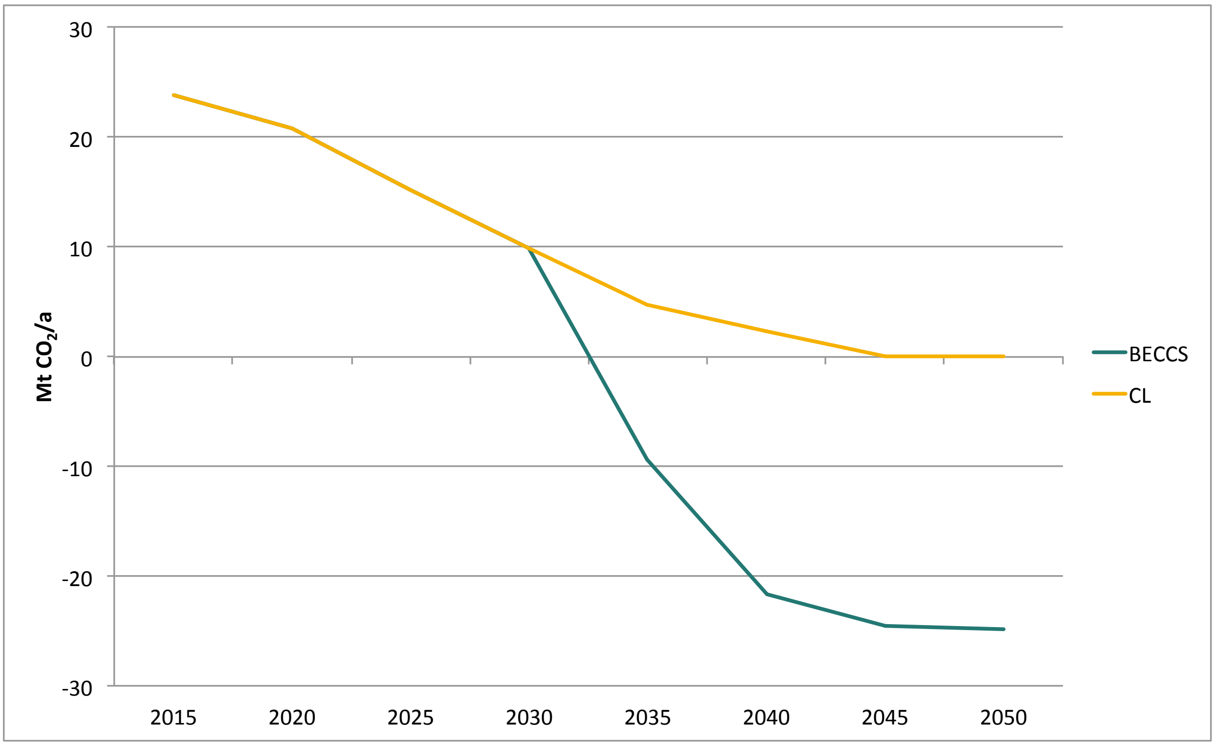


Figure 33: CO$_2$ emissions of the pulp and paper sector in the Carbon Looping and the BECCS case [source: own calculations]

6 Discussion of results and outlook

6.1 Building cross-sectoral scenarios

The main aim of WP 4.3 is to develop sectoral pathways. However, to derive some cross-sectoral results on the overall EU and on the regional level the sector cases are combined in the following to cross-sectoral scenarios. Figure 34 shows the two scenarios.

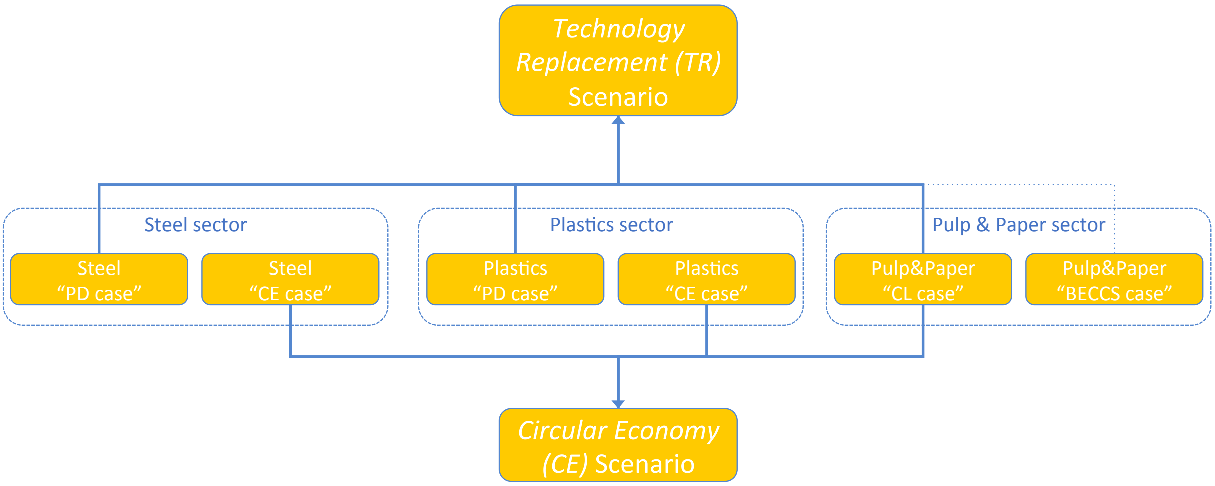


Figure 34: Scenario building by sector case combination

The two "producer-driven" (PD) cases for steel and plastics can easily joint to one scenario. For the pulp and paper sector such a case was not derived, because it seemed of little interest. However, the "Carbon Looping" (CL) case developed for the pulp and paper sector may be understood as "driven by the chemical industry". It has thus been combined with the two PD cases to form a "Technology Replacement Scenario". With this scenario name we refer to a scenario storyline developed in REINVENT WP 3.5, although the assumptions taken here do not completely fit to the developments described in WP 3.5.

An even more obvious combination of cases is the "Circular Economy Scenario" consisting of the two CE cases for steel and plastics and the "CL" case for pulp and paper.

The "BECCS case" for the pulp and paper industry would also fit to some degree to the "Technology Replacement" scenario. Therefore it is connected via a dotted line to this scenario in Figure 34. The line is only dotted, as in in both cases developed for plastics the plastics sector takes methanol from pulp and paper, which is only possible in the CL case and not in the BECCS case. The BECCS combination with the two PD cases thus gives not a consistent framework of quantitative results and will thus be discussed only briefly in a qualitative way.

Pulp and paper's "BECCS case", however, would fit to a "CCS scenario", combined with "CCS cases" for steel and plastics (as described in REINVENT D 4.2) or – in a lean CCS system – with a CCS case for *cement* industry, which is not part of the REINVENT focus sectors. Such a cross-sectoral CCS scenario is not discussed in WP 4.3.

6.2 Cross-sectoral results for the two scenarios

In both scenarios the aggregated final energy use of the three sectors showed in Figure 35 declines until 2030 due to energy efficiency investments and also due to more circular production (increased secondary production). There is a strong energy carrier shift from coal to electricity and natural gas use, which can be mainly attributed to primary steel making with the shift from the BF/BOF route to DRI.

After 2030, final energy use increases in both scenarios. It has to be stressed that this increase is mainly due to the balancing method: The paper industry exports 240 PJ of black liquor in 2040 and 520 PJ in 2050. This black liquor export has to be compensated by electricity use (e.g. for steam supply). The supply of black liquor based methanol to the plastics industry is however balanced as a feedstock use and thus not balanced here.

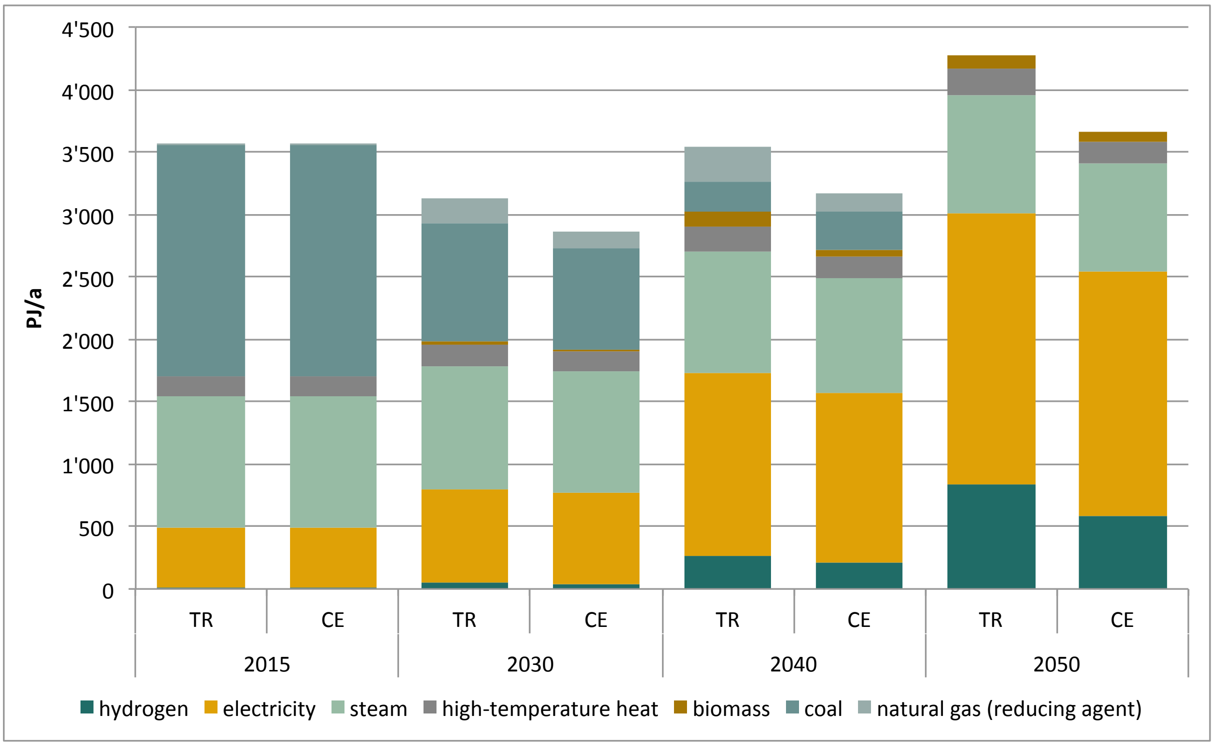


Figure 35: Final energy use of the three sectors in the TR and CE scenario (without fuel use for steam cracking) [source: own calculations]

Figure 36 displays the development of CO_2 emissions for the two scenarios. In 2030 the emission level is 35% lower in the TR scenario than 2015 and even 39% in the CE scenario. Such a development could not be seen in the bottom-up sector scenarios described in the earlier REINVENT Deliverable D4.2 where emission levels remained almost stable until 2030. The scenarios developed in the course of Work Package 4.3 can be thus seen as a further alignment of the sector scenarios to early GHG reduction requirements derived in the 1.5° scenario developed by PBL in WP 4.2.

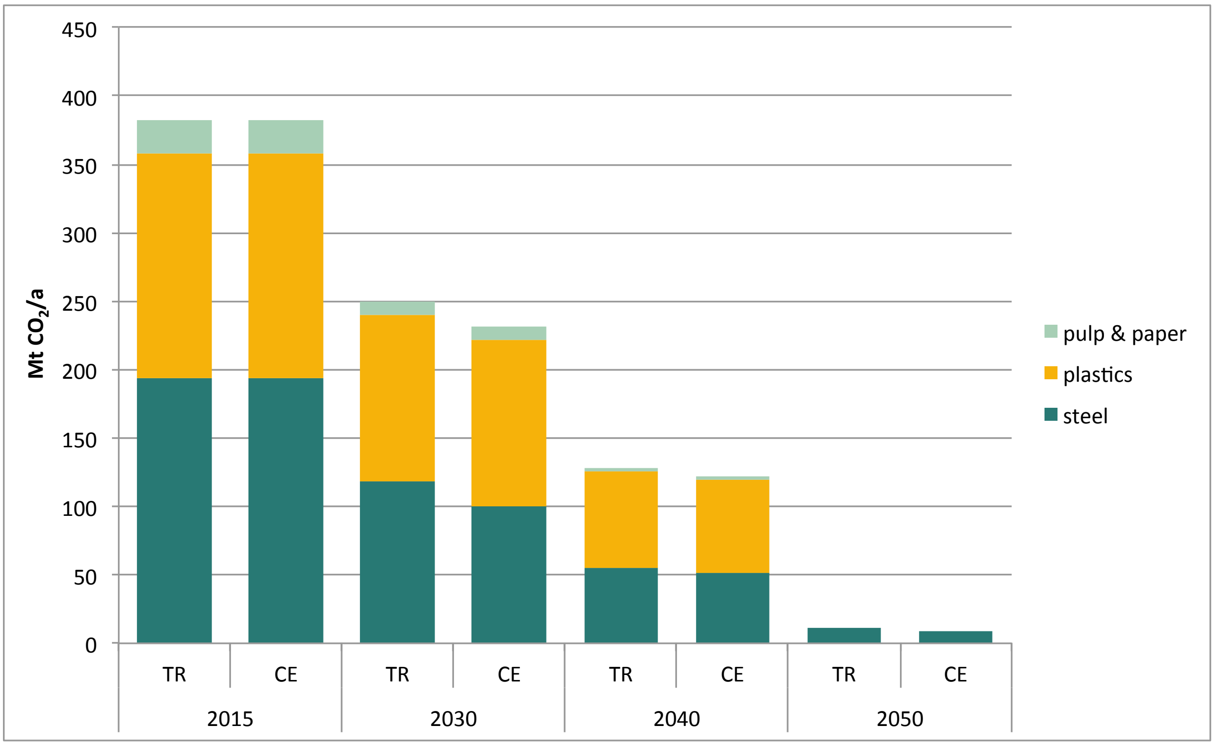


Figure 36: Development of CO_2 emissions in the two scenarios (incl. EOL emissions of plastics) [source: own calculations]

In 2040 almost 70% reduction are achieved and in 2050 only some emissions from the steel industry remain, which could be also omitted by the use of biogenic feedstock as anode material in the electric arc furnace.

It has to be stressed that the development described requires a lot of renewable energy supply, notably electricity and electricity-derived hydrogen. Energy supply could not be analysed yet in in this report, but availability was considered implicitly when making assumptions about the phase-in of technologies and with the assumptions on supply costs of renewable feedstock for the plastics industry.

A BECCS case for the pulp industry as described in section 5.2 would reduce final energy demand (namely electricity) in the pulp and paper industry and would result in net negative emissions of the sector. On the other hand, such a development would increase the import demand for other renewable feedstock, which would have to be imported from outside Europe, i.e. hydrocarbons derived from CO_2 taken from the atmosphere by the Direct Air Capture (DAC) technology.

6.3 National and regional implications

The following analysis is intended to give insight about the challenges for the individual energy systems of countries within the EU28 when decarbonising their heavy industry.

Table 10 shows the development of electricity demand of the three sectors in each country. As the countries differ in surface and population relative development is in many cases the more meaningful indicator. However, there are also large countries that have only little energy intensive industry, so the absolute numbers are relevant as well.

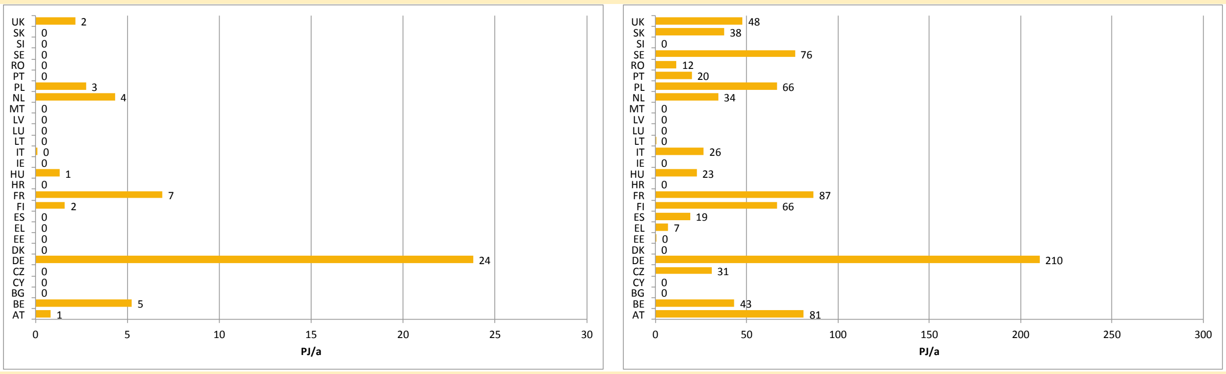
Table 10: Electricity demand of the three sectors in PJ/a in the two scenarios by country [source: own calculation]

state	TC					CE				
	2015	2030	2050	2030/2015	2050/2030	2015	2030	2050	2030/2015	2050/2030
AT	18	16	45	-11%	182%	18	18	63	0%	253%
BE	21	26	73	24%	178%	21	35	58	65%	65%
BG	1	1	1	-9%	30%	1	1	1	-9%	40%
CZ	6	6	21	14%	224%	6	8	21	44%	152%
DE	129	171	427	33%	150%	129	164	327	28%	99%
DK	2	2	4	-2%	130%	2	2	4	-2%	130%
EE	1	1	2	-9%	71%	1	1	2	-9%	71%
EL	3	3	5	-22%	114%	3	2	1	-36%	-30%
ES	39	44	88	14%	101%	39	38	76	0%	98%
FI	73	55	139	-25%	153%	73	53	136	-27%	156%
FR	53	65	140	22%	117%	53	54	103	2%	90%
HR	1	1	2	-23%	103%	1	1	2	-29%	118%
HU	5	4	16	-15%	310%	5	5	10	-3%	126%
IT	62	68	113	10%	65%	62	61	92	-1%	50%
LT	0.4	0.4	1.5	9%	265%	0.4	0.9	2	125%	129%
LU	5	5	4	20%	-34%	5	4	3	-4%	-25%
LV	0.2	0.1	0.3	-13%	145%	0.2	0.1	0.3	-13%	145%
NL	15	29	83	93%	187%	15	22	54	48%	145%
PL	22	27	87	21%	226%	22	27	66	23%	144%
PT	17	19	60	16%	210%	17	18	58	10%	218%
RO	3	4	12	17%	213%	3	3	8	1%	147%
SE	95	70	202	-27%	191%	95	69	198	-27%	187%
SI	3	4	6	8%	60%	3	3	6	0%	68%
SK	5	7	36	21%	446%	5	6	24	18%	282%
UK	24	26	62	8%	136%	24	26	46	5%	79%

The highest absolute increases may be observed in Germany, Sweden, Finland, the Netherlands and Poland. Germany is a densely industrialised country and so are the Netherlands and Belgium. Density in the two Nordic countries is less high but pulp industry plays an important role. Poland has some strong industrial heavy industry clusters, in particular steel and chemicals industry.

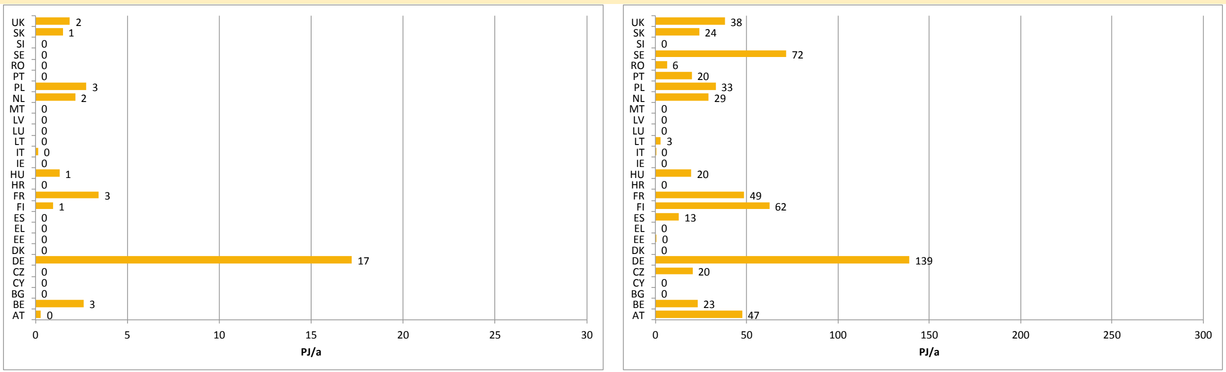
Highest relative increase rates can be observed in Slovakia and Hungary, but both starting from a low level of electricity use. The analysis shows however, that also the countries of the Visegrád group (Poland, Hungary, Czech Republic, Slovakia) will have a strong need for renewable electricity in the future when electrifying their industry. A circular economy will help to lower electricity demand in almost every country in the EU. Some deviating developments where increases are higher in the CE than in the TR scenario are in relatively small countries and due to specific developments in the plastics sector, where the reinvestment in new technologies was modelled bottom-up. For such small countries the deviation may be attributed to just one investment and cannot thus not be rated as robust.

Development of hydrogen use in the three sectors is shown in Figure 37.



TR scenario

2030 | 2050



CE scenario

2030 | 2050

Figure 37: H_2 use in the two scenarios 2030 and 2050 in PJ/a [source: own calculation]

Highest demands in both scenarios are in Germany, France, Austria, Sweden, Finland, the UK and Poland. In regard to the potentials available for inland renewable electricity production in particular Germany, Austria and Poland need an import strategy for hydrogen to keep their heavy industry alive. Belgium and the Netherlands are small countries with relative low renewable electricity potentials but very strong chemical clusters around the two ports or Antwerp and Rotterdam. Import will be an issue here as well but can be easier be implemented at the ports.

The UK on the other hand has the potential to reindustrialize because of the high renewable potentials combined with a relative low industrial demand today. If Sweden succeeds in attracting additional DRI making capacities sited at the mines in the North, and supplying DRI as an intermediate product to the Western and Central Europe, hydrogen demand would be even higher than indicated (and possibly lower in Germany or Poland).

The two maps on the next pages illustrate the density of demand for electricity and hydrogen. Only sites of the steel and plastics industry are considered here. Pulp and paper industry's future electricity and hydrogen demand will result in additional hot spots, especially in Sweden and Finland (but also Portugal), which cannot be displayed, as pulp and paper mills are not explicitly covered per site in the WISEE edm database.

The maps indicate some clusters: The most prominent one is the region of Flanders, South Holland and Western Germany, which is also known as Europe's "petrochemical triangle", with the three corners of Antwerp, Rotterdam and Rhine/Ruhr. Another important cluster is the Rhône delta around

Marseille. Both regions have a strong diversity in heavy industries and differentiated value chains, especially in the plastics sector. If the structure in plastics demand (namely the portfolio of plastics sorts) does not change too much in favour of new plastic sorts, these clusters will remain robust because of the high synergies they provide.

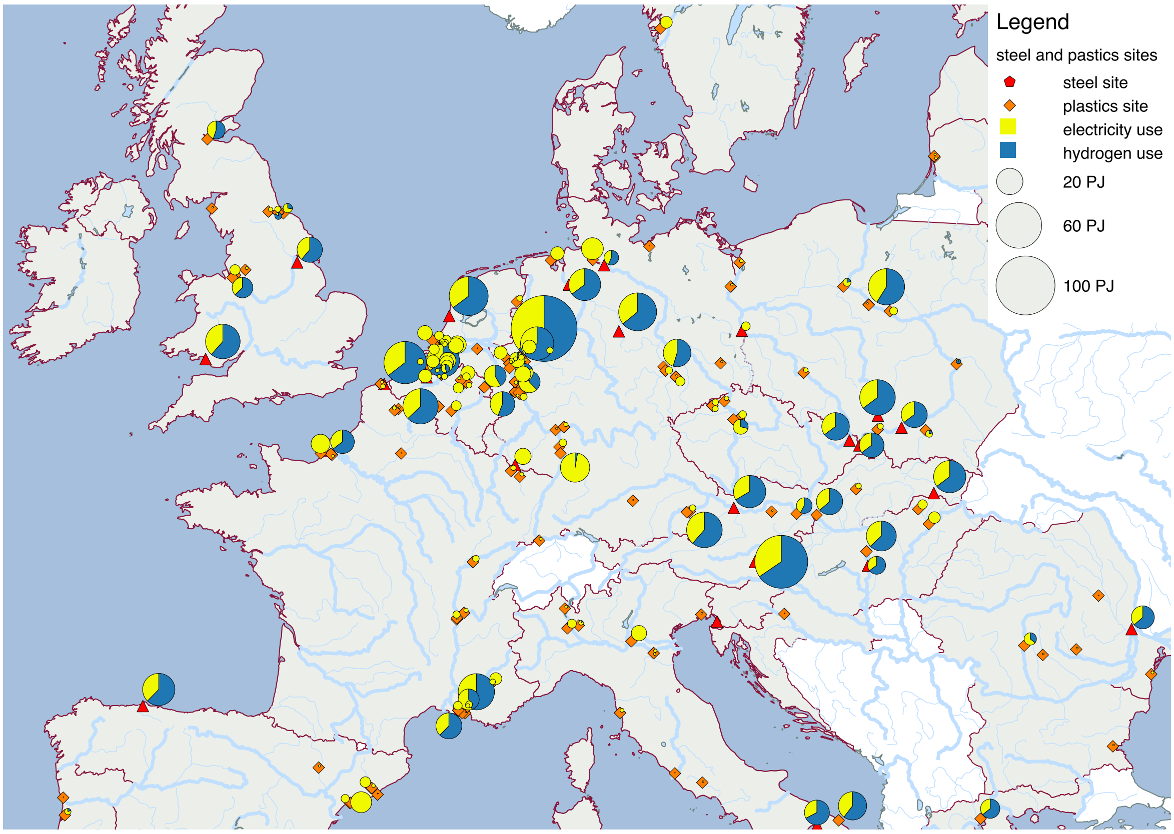


Figure 38: Map on electricity and hydrogen hot spots of the steel and plastics sector in the TR scenario (including electricity use for steam supply, without electricity use for hot rolling) [source: own map]

The region around the borders of Poland and the Czech Republic could be described as a "steel region", which is indicated in the maps by an agglomeration of energy demand bubbles. The future of these sites as primary steel making sites will depend on the supply of hydrogen and the robustness of demand in the region (e.g. from automotive). Today these sites profit from the nearby coking coal mines.

Other heavy industry sites are rather single sites and not agglomerations. Most often they have a clear focus on one or two production routes. Locations at the coast will not lose their competitive advantage over inland sites. They are in general much more flexible in their access to new energy carriers or feedstock, which could be observed in recent years for steam cracking sites at the coast which were able to react to very low prices for ethane form the U.S. and converted their plants to flexible crackers.

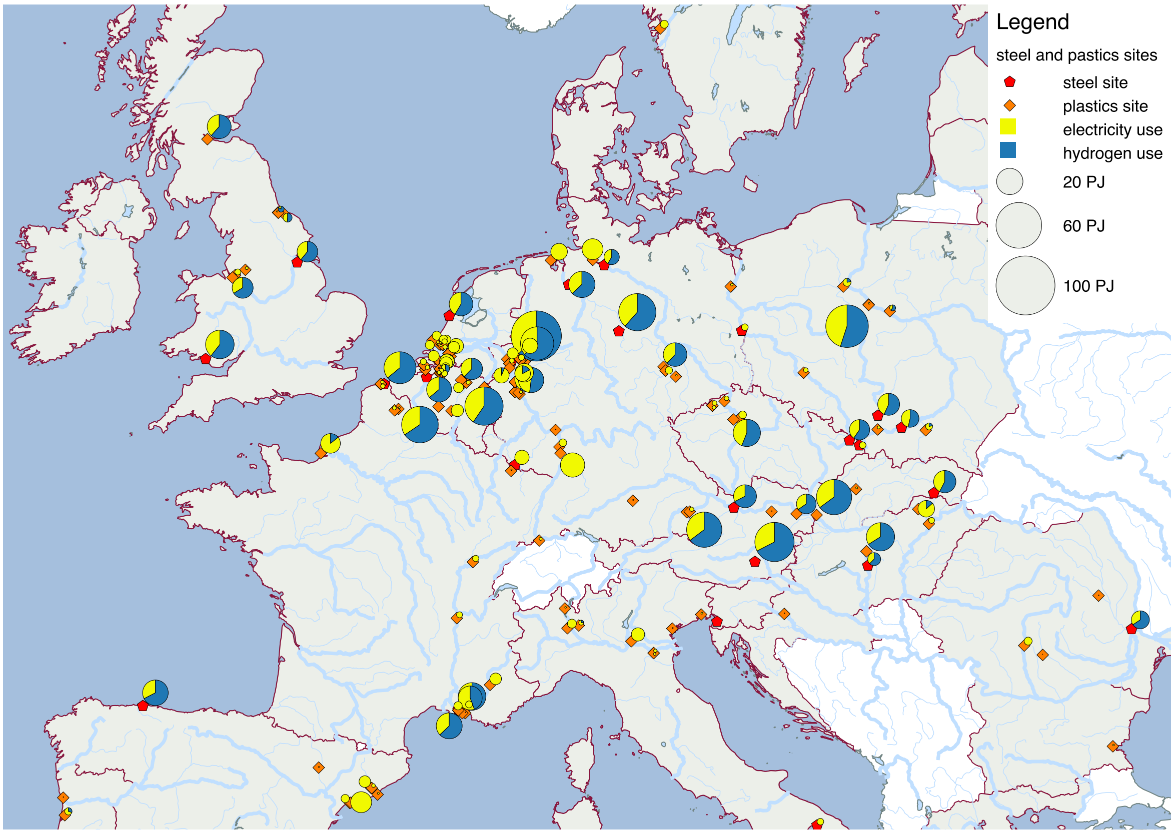


Figure 39: Map on electricity and hydrogen hot spots of the steel and plastics sector in the CE scenario (including electricity use for steam supply, without electricity use for hot rolling) [source: own map]

6.4 Outlook

Work in REINVENT WP 4.3 documented in the report at hand tried to deepen insights on the three sectors of steel, plastics and pulp and paper as well as on possible cross-sectoral effects and regional impacts within the European Union at the level of member states or regions.

The discussion of the results showed that the items of the research agenda mentioned in the introduction chapter could be addressed in WP 4.3, but also revealed some shortcomings in the analysis (and the general scientific discourse on industry decarbonisation) that leave potential for further analysis within REINVENT and beyond the project. They shall be discussed briefly in the following.

6.4.1 Energy system integrated scenarios

An important next step within REINVENT WP 4 is the integration of the sectoral insights into integrated energy and emission scenarios for the whole system (and the whole world). There have been various potential and scenario studies showing that electricity demand at levels shown in our scenarios can be met by techno-economical potentials, but analysis in WP 4.3 cannot yet provide insights of the impacts of such scenarios on the electricity system or vice versa.

Such a system integration of the energy supply system and industry scenarios will be provided by PBL’s IMAGE model in WP 4.4, however, at a lower level of technological detail.

6.4.2 Best practices and technological and social innovations

One item of the research agenda for WP 4 expressed as an interim conclusion of D4.2 is the “research on best practices and technological and social innovations”, meaning that quantitative scenario making needs to be better informed about the uptake of innovations and their diffusion. In

WP 4.3 a deeper understanding regarding implementation speed for the concrete cases could be reached based on intensive stakeholder and expert discussions. However, an actual improvement of the models itself could not be achieved yet. In fact, one shortcoming of the REINVENT overall project design is the lack of an explicit modelling of innovation systems, which could be addressed e.g. by agent-based modelling (ABM). The actual uptake of innovations can thus not be directly modelled in REINVENT. Instead, the phase-in of new technologies is derived qua assumption (object of discussion in the workshops) or due to simplified economic considerations.

This shortcoming is less relevant when studying the production systems of steel, plastics and paper industry with rather simple systems of only a few agents who typically behave in a very strategic way. In regard to innovations along the value chain including recycling systems and product design (or also the finance sector) agent-based modelling (ABM) could yet offer additional insights.

6.4.3 Possible role of product substitution

The changes in material production costs will result in relative price changes between steel, plastics and paper (not to forget aluminium and glass). In various use categories like packaging materials can be substituted with each other and relative price changes will probably favour paper use in the future as price increases due to energy cost increases will be lower there. The absolute use potential of paper is, however, limited due to biomass availability. Also competing uses for wood, e.g. as a building material or to supply feedstock for fuel production may exert price pressures on paper industry.

Impacts of decarbonised and de-fossilized basic material supply on product substitution are not addressed by the work in REINVENT WP 4, but should be an issue in future research on industry decarbonisation.

6.4.4 Infrastructure implications

The actual implementation of a deep decarbonisation requires various new infrastructures and infrastructure adaption or amendment. Geographical issues around the production system for steel, plastics and paper have been discussed in the report at hand to some degree and some core infrastructures like the pipelines for chemicals have been explicitly addressed.

A thorough infrastructure analysis that takes de-fossilization of heavy industry into account is not part of the REINVENT research programme, but should be an important issue in forthcoming projects. Some first insights for several European heavy industry clusters have been derived in the Climate-KIC funded project “INFRAneeds”[4], which has been conducted during 2019 by Wuppertal Institute and European Climate Foundation.

6.4.5 Carbon balances and optimized carbon looping

Competition for resources but also possible synergies in a GHG neutral production system between chemicals, fuel production, chemical pulping (paper industry) and direct use of wood (e.g. in construction) with the respective (hydro-)carbon balances have not yet been studied in depth at an overall system level. So there is potential for further analysis on carbon looping and on the optimal use of biogenic carbon in the future.

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[4] See the project website at https://wupperinst.org/en/p/wi/p/s/pd/818/.

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8 Annex

Annex 1: List of emission factors used in chapter 4

activity	unit	2020	2030	2040	2050
naphtha (EOL)	t/t	3.1	3.1	3.1	0
ethane (EOL)	t/t	2.9	2.9	2.9	-
propane (EOL)	t/t	3.0	3.0	3.0	-
electricity (indirect)	t/GJ	93	75	0	0
steam (indirect)	t/GJ	62	56	19	0
HT heat (direct)	t/GJ	56	56	28	0

Annex 2: Short description of WISEE production stock database

The database on European production stock for energy intensive industry used in WP 4.3 modelling comprises information on plant capacities, plant age (for some core processes), specific energy as well as feedstock consumption or specific production of by-products (e.g. hydrogen from chlorine electrolysis).

Every plant is attributed to site and the respective site information comprises GIS coordinates and an attribution to a EU member state.

The database hierarchy can be described like this

- sector (according to NACE code)
  - industrial geographical cluster (cluster of interconnected sites)
    - site (GIS, attribution to steam and hydrogen grid)
      - production process (attributed to site)

For each single production process an efficiency category is chosen according to the year of commissioning. Most processes in the database are categorized as default, which means that they are rated as a European standard technology according to the mean in the years 2000-2005 (before the introduction of the ETS). If a process has had a revamp with a major retrofit after the year 2005 it is categorized as best-available technology (BAT). The technology status of BAT is derived from the most recent BREF papers published by the JRC (see https://eippcb.jrc.ec.europa.eu/reference/). For petrochemical processes a study be the IEA (2009) has been used as reference.

For the pulp and paper sector we could not rely on the WISEE database as the processes are accounted for Germany only. Instead, the e-prtr database by the EEA was used to identify pulp and paper making sites all across Europe.

Annex 3: Short description of WISEE edm-D

WISEE edm-D calculates energy and feedstock use for several energy intensive industrial branches at a plant level. It has a direct interface to the production stock database described in Annex 2. Thus it can be used flexibly at any regional level to derive scenarios, e.g. for just one cluster or for the whole

EU. Due to the site information provided for each plant in the database steam and hydrogen balances can be derived at a site level balancing out gross use in consuming processed and gross production in producing processes, even if the model is applied for the whole EU.

WISEE edm-D has been used in various projects, e.g. for the Rotterdam Harbour's industrial cluster, for the German states of North Rhine Westphalia and Rhineland Palatine as well as for Germany as a whole and in the REINVENT project for the whole EU.

Annex 4: Short description of WISEE edm-I

Petrochemical industry will be one of the remaining sectors in a climate neutral economy still handling hydrocarbon material to manufacture polymers. Concepts of a climate neutral chemical industry stress the need to consider the potential end-of-life emissions of polymers produced from fossil feedstock and draft the vision of using renewable electricity to produce hydrogen and to use renewable (hydro)carbon feedstock. The latter could be biomass, CO_2 from the air or recycled feedstock from plastic waste streams.

The cost-optimization module WISEE edm-I (as part of WISEE edm model framework) simulates at which sites investments of industry in the production stock could take place in the future. Around 50 types of products, the related production processes and the respective sites have been collected in a database (see Annex 2). The processes included cover the production chain from platform chemicals via intermediates to polymers. Pipelines allowing for efficient exchange of intermediates between sites are taken into account as well. The model draws on this data to simulate capacity change at individual plants as well as plant utilization. Thus a future European production network for petrochemicals with flows between the different sites and steps of the value chain can be sketched.

The scenarios developed by the model reveal how an electrification strategy could be implemented by European industry over time with minimized societal costs. Today's existing assets as well as geographical variance of energy supply and the development of demand for different plastic sorts are the major model drivers.

Annex 5: Short description of WISEE Plastic STOCK

The WISEE Plastic STOCK module provides a detailed representation of plastics use and waste streams in Europe. It accounts for five plastic conversion sectors (packaging, construction, automotive, electric and electronics, and other). Future plastics demand according to a baseline development 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. WISEE Plastic STOCK 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.

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.