sEEnergies

QUANTIFICATION OF SYNERGIES BETWEEN ENERGY EFFICIENCY FIRST PRINCIPLE AND RENEWABLE ENERGY SYSTEMS

D3.6 Energy efficiency potentials on top of the frozen efficiency scenario

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Authors	**Katerina Kermeli (UU)** **Wina Crijns-Graus (UU)**
Reviewer	**Dirk Saelens (KU Leuven)** **Ulrich Reiter (TEP)**

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Acronyms & Abbreviations

Term	Description
BF	Blast furnace
BOF	Basic oxygen furnace
BF/BOF	Blast furnace/Basic oxygen furnace
EAF	Electric arc furnace
EED	Energy Efficiency Directive
EJ	Exajoule
ESD	Effort Sharing Decision
EU	European Union
EU ETS	European Union Emission Trading System
GJ	Gigajoule
HRE	Heat Roadmap Europe
GJ	Gigajoule
PJ	Petajoule
SEC	Specific energy consumption

1 Introduction

In the sEEnergies project, the detailed analysis of the industrial sector is based on the latest EU projections for the development of energy demand up to 2050 (European Commission, 2016 and 2019). The reference scenario in European Commission (2016) includes final energy demand projections per industrial sub-sector and EU country, while capturing current policies and market trends. However, it does not give insights into the extent to which energy efficiency potentials are already implemented. For this reason, this analysis focuses on constructing a frozen efficiency scenario that considers the same structural changes as the reference scenario in European Commission (2016), but with no energy efficiency improvements. The main aim is to understand the impact of structural changes and energy efficiency in the total final energy projections. To assist the comparison, the final energy demand in the reference scenario is decomposed into volumes (tonnes of product) and energy efficiency.

Two scenarios are analysed:

- Reference scenario: The reference scenario is based on the reference scenario from European Commission (2016). It shows the energy demand projections per industrial sub-sector and EU country. The main assumption is that current policies are continued but not tightened.
- Frozen efficiency scenario: The frozen efficiency scenario assumes that no energy efficiency or technological changes take place in the manufacture of industrial products. It allows however for socio-economic changes (i.e. industrial value added and production volumes).

This document summarizes the method and assumptions made to construct the reference and frozen efficiency scenarios. In addition, it compares the final energy demand projections made in these two scenarios with the main purpose to distinguish the impact of socio-economic changes and energy efficiency changes on the energy demand projections.

As a following step, it explores four types of alternative future scenarios, able to substantially decrease the final energy demand and/or deeply reduce industrial greenhouse gas emissions. The developed scenarios have varying degrees of technology diffusion rates and varying types of technological innovations to construct different energy demand pathways for the EU industry. The four mitigation scenarios are:

- BAT scenario: The BAT scenario assumes that Best Available Technologies (BATs) are widely adopted across all industrial sub-sectors.
- BAT (high recycling) scenario: This scenario has the same assumption as the BAT scenario, but it also allows for material recycling improvements in main industries (e.g. increased shares of steel production from scrap).
- Electrification scenario: In this scenario the focus is on the implementation of technologies that can switch the demand for fuel into electricity.
- Hydrogen scenario: In this scenario the focus is the implementation of technologies that can switch the demand for fuel into hydrogen.

Main results:

- **Final energy demand for all EU 28 countries per industrial sub-sector in the reference and the frozen efficiency scenarios.** Reported energy demand is up to 2050 with 5-year intervals, per fuel type.
- **Final energy demand for heating and cooling, for all EU 28 countries per industrial sub-sector.** Reported energy demand is up to 2050 with 5-year intervals, per temperature level and per fuel type for two scenarios.
- **Autonomous and policy induced energy efficiency improvement included in the reference scenario.** These are the energy savings already realized in the reference scenario. Autonomous refers to energy efficiency improvement which occurs due to technological developments. Each new generation of capital goods is likely to be more energy efficient than the one before.
- **Final energy demand for all EU 28 countries per industrial sub-sector in four mitigation scenarios.** Reported energy demand is for 2030 and 2050 per industrial sub-sector, industrial product and fuel types.
- **Energy savings per industrial sub-sector.** The energy savings for each industrial sub-sector, and for all main products in the four mitigation scenarios for the EU 28.

Results on the costs of conserving energy and on the overall required investment costs for all four mitigation scenarios will be reported in Deliverable 3.4 of the sEEnergies project.

2 WP3 and link to other WPs in sEEnergies

The starting point for WP3 is the construction of the baseline scenarios. Two baseline scenarios are developed i) the Reference scenario and ii) the Frozen Efficiency scenario. As a next step, all technologies/measures that could considerably decrease the energy demand are identified and used to build the Energy Efficiency (named BAT in this analysis) scenarios. In addition, the main electrification and hydrogen technologies are identified and implemented in the Electrification and the Hydrogen scenarios.

For all technologies we identify the 2030 and 2050 energy savings potential (for both fuel and electricity) and the fuel switch potential (i.e. from fossil fuels to electricity and from fossil fuels to H_2). Along with the implementation rates of each of the technologies we determine the associated investment costs. This allows for the development of cost-supply curves for each of the four scenarios and for all EU countries. Furthermore, the excess heat available from the main industrial processes is calculated by combining excess heat data (in GJ/tonne) from WP5 and activity data from WP3 for two scenarios, the Frozen Efficiency and the BAT scenarios. The dotted lines in Figure 1 represent data exchanges between the different WPs.

The final energy demand, the technology impact on energy use, the cost curves and the excess heat are fed into the IndustryPLAN model, that forms a part of the EnergyPLAN model.

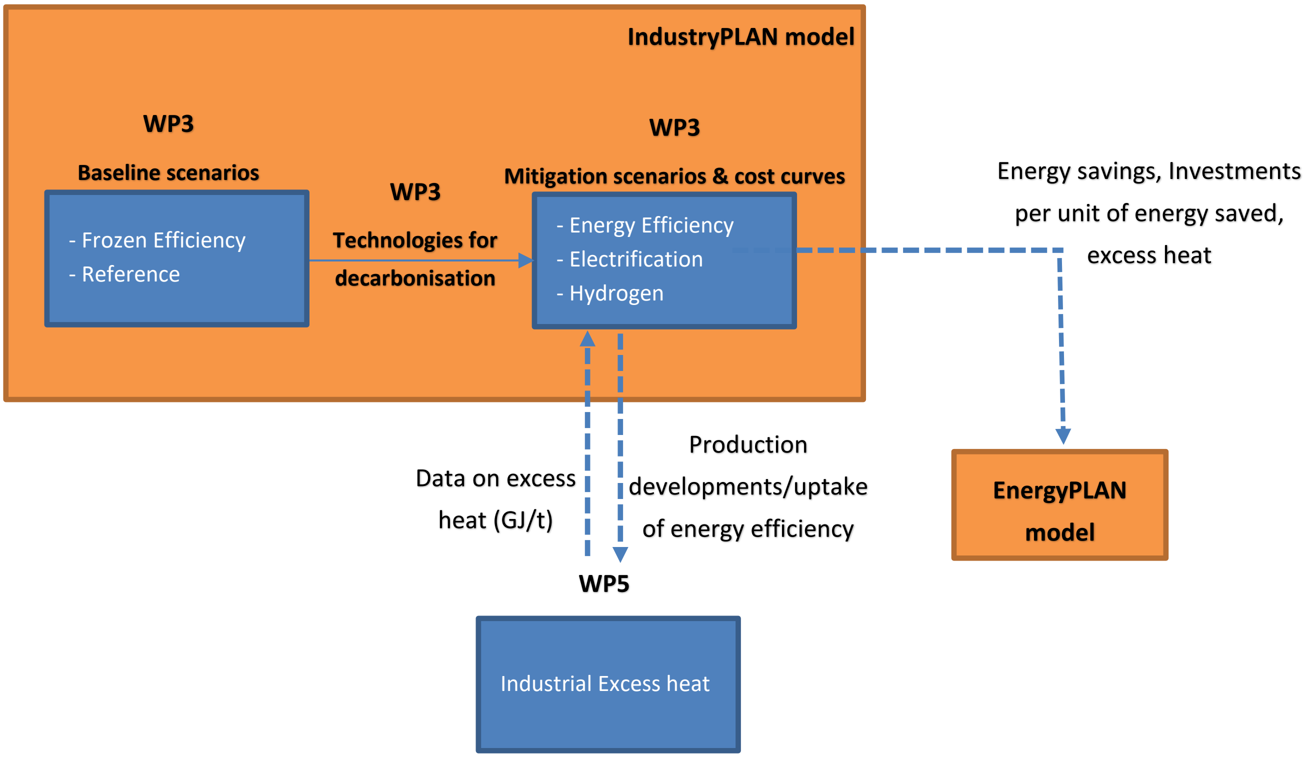

Figure 1 Interlinkages between WP3 and other WPs in sEEnergies.

3 Overview of the approach

3.1 The Reference and the Frozen Efficiency scenarios

Three main data sources are used to develop the Reference scenario:

(1) The EU Reference Scenario 2016 (European Commission, 2016) is used for the final energy development of industries in the period 2015-2050 (data is available for 5-year intervals). It is the most recent scenario for the EU that contains data on a per country and per sector level. Per industrial sub-sector (iron and steel, non-ferrous metal, chemicals, non-metallic minerals, paper and pulp and other) it only includes total final demand. For the industry as a whole, the energy demand is disaggregated into coal, oil, natural gas, electricity and other.

(2) IEA (2016) is used for the breakdown of final energy demand per source (coal, peat, oil, natural gas, electricity, biomass and waste, geothermal, solar, heat and others) per industrial sub-sector, for the base year 2015. For future fuel mixes the shares are either kept constant or adapted, depending on the development of different production routes (e.g. more electric steel than integrated steel).

(3) Heat Roadmap Europe 4 (HRE4) (2017) is used for estimating the share of final energy demand per industrial sub-sector that is used for heating and cooling and at which temperature level.

The resulting final energy demand data for industries includes energy used in blast furnaces and coke ovens but excludes feedstocks (e.g. in the petrochemical industries) and primary energy used to produce purchased electricity. Furthermore, refineries are not included.

The EU Reference 2016 scenario includes policies and measures adopted in the EU in 2014 and Directive amendments made in 2015 (European Commission, 2016). The availability of EU Emissions Trading System (ETS) allowances faces an annual decrease following current Directive provisions and industrial energy efficiency improves reflecting recent policies such as Ecodesign and labelling and the Energy Efficiency Directive (EED). The EU wide greenhouse house gas emission (GHGs) reductions from the Effort Sharing Decision (ESD) are assumed to be achieved in the reference scenario. The industrial GHG emission intensity slightly decreases (by 2%) in 2020 (compared to 2010) to more drastically decrease in 2030 (27%) and 2050 (51%). This is the result of increased energy efficiency, switch to the production of higher value-added industrial products, slow growth of energy intensive industries, and the shift to lower carbon intensive fuels.

Based on the reference scenario a frozen efficiency scenario is developed where the specific energy consumptions (SEC) (in GJ/tonne) remains fixed. The difference between the reference scenario and the frozen efficiency scenario is therefore equal to the (autonomous and policy induced) energy-efficiency improvement in the reference scenario. This provides a good basis for the estimation of the energy efficiency improvement potentials in comparison to the frozen efficiency and reference scenario.

The frozen efficiency scenario is based on:

- Value added assumptions in EU Reference 2016 scenario (European Commission, 2016).
- Estimated production data (based on European Commission (2016), HRE4 (2017) and other sources (see Table 1)).
- SEC data from HRE4 (2017) and other literature.

Table 1 shows the sources used for the activity developments.

Table 1 Summary of main assumptions for projections of industrial activity.

Parameters	Sources	Main assumptions for projection
Industrial value added	EU Ref 2016 (European Commission, 2016)	same as EU Ref.
Iron and steel	POTEnCIA (Mantzos et al, 2019); Worldsteel, 2018	Reference scenario: growth same as POTENCIA; frozen efficiency scenario: total steel growth same a POTENCIA and Electric Arc Furnace (EAF) share remains fixed to the 2015 level.
Cement	POTEnCIA (Mantzos et al, 2019); GCCA, 2020; ECRA, 2017	Reference scenario: cement growth same as in POTENCIA and clinker growth at a slower pace; frozen efficiency scenario: cement and clinker grow at the same pace.
Chemicals	EU Ref 2016 (European Commission, 2016)	Fertilizers and inorganic chemicals stabilize and slightly decline in later years, methanol and ethylene experience strong growth.
All other industrial products	EU Ref 2016 (European Commission, 2016); HRE4 (2017)	No radical changes.

The outcome is for the reference and the frozen efficiency scenario for the years 2015, 2020, 2025, 2030, 2035, 2040, 2045 and 2050 per EU country:

-total final energy demand per industrial sub-sector (split into coal, peat, oil, natural gas, electricity, biomass and waste, geothermal, solar, heat and others),

-final energy demand for heating and cooling per industrial sub-sector (per temperature category).

Input data per industrial sub-sector

Figure 2 shows how the industrial value-added changes in the 2015-2050 period in the reference scenario in the different EU countries. The data are taken from the EU Reference scenario that reports industrial value-added projections per country and per main industrial sub-sector (European Commission, 2016). The twelve countries in Figure 2 were responsible for 90% of the 2015 industrial value added. Only five countries, Germany, Italy, France, UK and Spain were responsible for 70% of the EU28 value added in 2015, a share that is projected to drop to 65% by 2050. Overall, in the 2015-2050 the industrial value added in the EU is projected to grow by 45%. In most countries, industrial value added grows stronger in the 2015-3030 period[1] (see Table 2).

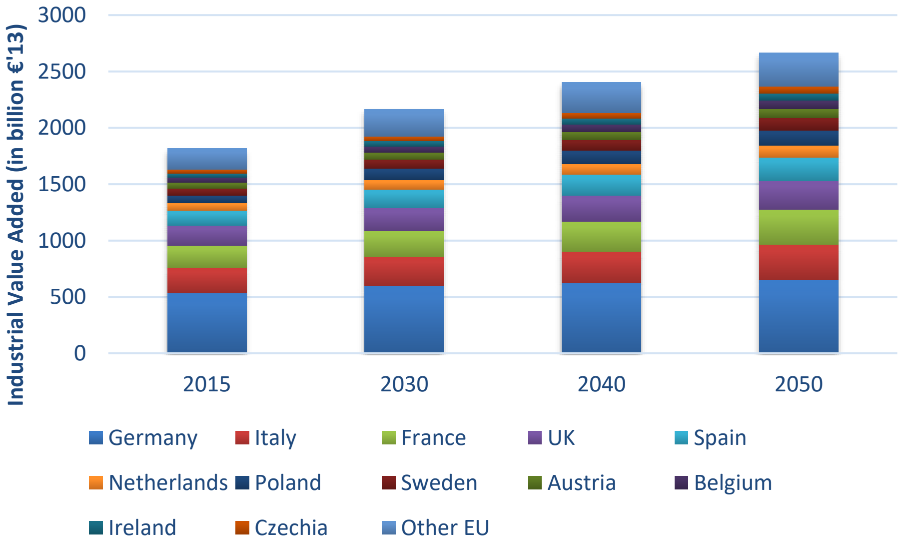

Figure 2 Industrial value added per EU country (European Commission, 2016)

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[1] The industrial value added projections used in this analysis do not consider the impact that the CoViD pandemic (taking place in 2020) may have on the future growth of the EU industry.

Table 2 Industrial value added per country and associated growth rates (European Commission, 2016). (unit: billion €'13)

Countries:	2015	2030	% 15-30	2040	% 30-40	2050	% 40-50
Germany	535	602	13%	624	4%	653	5%
Italy	227	254	12%	280	10%	313	11%
France	194	230	19%	266	16%	310	16%
UK	180	203	13%	230	13%	256	11%
Spain	130	165	27%	187	14%	207	11%
Netherlands	70	83	19%	92	10%	104	13%
Poland	66	102	54%	122	19%	135	11%
Sweden	61	78	30%	94	19%	112	19%
Austria	52	63	20%	70	12%	78	11%
Belgium	46	55	20%	66	20%	78	18%
Ireland	36	47	32%	54	15%	62	15%
Czechia	34	43	29%	51	17%	59	17%
Other EU	189	238	26%	270	13%	299	11%
EU28	1,818	2,164	19%	2,405	11%	2,665	11%

In Figure 3, the industrial value added in the EU28 is broken down per industrial sub-sector. The main contributor both in 2015 and 2050 is Engineering, responsible for 36% and 45% of total value added, respectively. The most energy intensive industries, pulp and paper, non-ferrous metals, non-metallic minerals and iron steel are responsible for 12% of the value added in 2015, much lower than 16% in 1995, and their share is projected to further decrease to 11% by 2050.

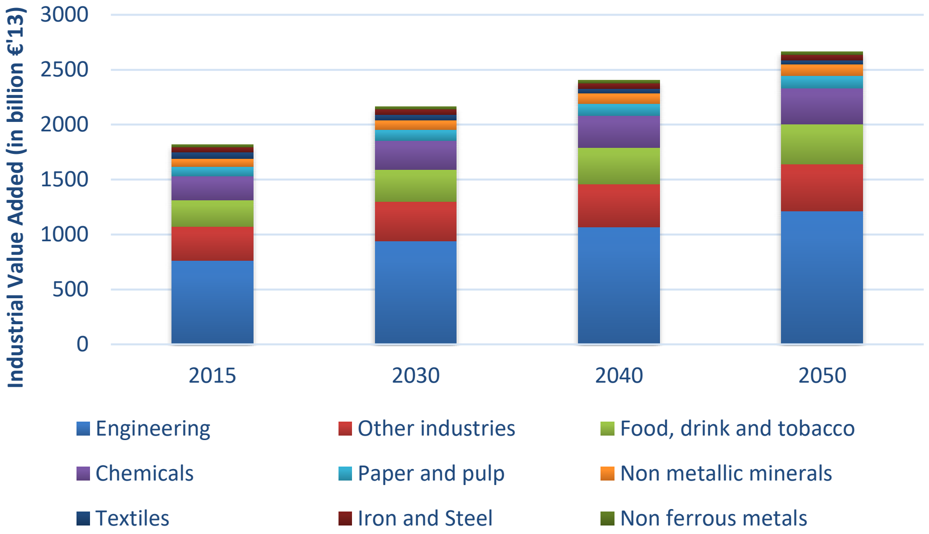

Figure 3 Industrial value added per industrial sub-sector (European Commission, 2016)

Table 3 shows the production developments of important industrial products in the Reference scenario. Most products experience an increase in production in the 2015-2030 period while in the 2030-2050 period the bulk seem to stabilize. A significant part of energy intensive products remains in the EU area (European Commission, 2016), so there is no expected significant decrease in production.

Table 3 Production developments in the EU28 in the Reference scenario (in ktonnes).

	2015	2030	% 25-30	2040	% 30-40	2050	% 40-50
Chemicals							
Carbon black	998	1,121	12.3%	1,143	2.0%	1,166	2.0%
Ethylene	16,810	18,091	7.6%	18,398	1.7%	18,306	-0.5%
Methanol	1,438	1,725	20.0%	1,768	2.5%	1,812	2.5%
Ammonia	17,394	18,146	4.3%	18,146	0.0%	18,137	0.0%
Soda ash	6,025	6,323	4.9%	6,350	0.4%	6,252	-1.5%
Iron and steel							
BF/BOF steel	100,864	104,949	4.1%	104,464	-0.5%	103,989	-0.5%
Pig iron	93,596	97,396	4.1%	96,914	-0.5%	96,772	-0.1%
Rolled steel	150,924	143,279	-5.1%	130,222	-9.1%	119,453	-8.3%
EAF steel	65,429	71,327	9.0%	74,437	4.4%	77,575	4.2%
Coke oven	32,586	31,981	-1.9%	31,631	-1.1%	31,469	-0.5%
Ferrous metals casting	10,185	10,912	7.1%	10,938	0.2%	11,091	1.4%
Nonferrous metals							
Aluminium primary	2,242	2,422	8.0%	2,396	-1.0%	2,398	0.1%
Aluminium secondary	3,300	3,488	5.7%	3,447	-1.2%	3,438	-0.3%
Nonferrous metals casting	3,672	3,972	8.2%	3,972	0.0%	3,972	0.0%
Non-metallic minerals							
Cement	168,170	200,917	19.5%	202,227	0.7%	204,500	1.1%
Flat glass	11,617	12,846	10.6%	13,147	2.3%	13,387	1.8%
Container glass	15,317	15,844	3.4%	14,972	-5.5%	14,149	-5.5%
Pulp and paper							
Paper	91,505	99,226	8.4%	100,369	1.2%	101,041	0.7%
Tissue paper	7,175	7,762	8.2%	7,851	1.1%	7,889	0.5%
Graphic paper	34,566	37,041	7.2%	37,325	0.8%	37,609	0.8%
Board and packag. Paper	46,114	49,512	7.4%	50,070	1.1%	50,606	1.1%
Chemical pulp	25,582	27,000	5.5%	27,315	1.2%	27,693	1.4%
Mechanical pulp	8,236	8,712	5.8%	8,796	1.0%	8,939	1.6%
Recovered fibre pulp	21,294	22,489	5.6%	22,729	1.1%	23,247	2.3%

The production volumes used in the reference and the frozen efficiency scenarios are the same, except in two cases:

i) **the clinker produced in the cement industry.** In 2015, the average clinker content in the EU was 76% (GCCA, 2020). In the EU Reference scenario, it is assumed that the potentials of using recycled materials is exhausted (European Commission, 2016). We thereby assume that the clinker content in the reference scenario drops to 66%, which the lowest clinker contents used currently in the EU (ECRA, 2017). In the frozen efficiency scenario, the clinker content remains stable at 74% (current level). Figure 4 shows the projected developments in cement and clinker production in the two scenarios.

ii) **the share of steel produced with the electric arc furnace route**. In 2015, the share of the more energy efficient steel production route that uses an electric arc furnace (EAF) was

39% (Worldsteel, 2018). In the reference scenario, the share of EAF steel is projected to account for more than 42% of total steel production (Mantzos et al., 2019). In the frozen efficiency scenario, we assume that the EAF share remains stable at 39% in the whole period analysed. Figure 5 shows the steel production with the different routes under the two scenarios.

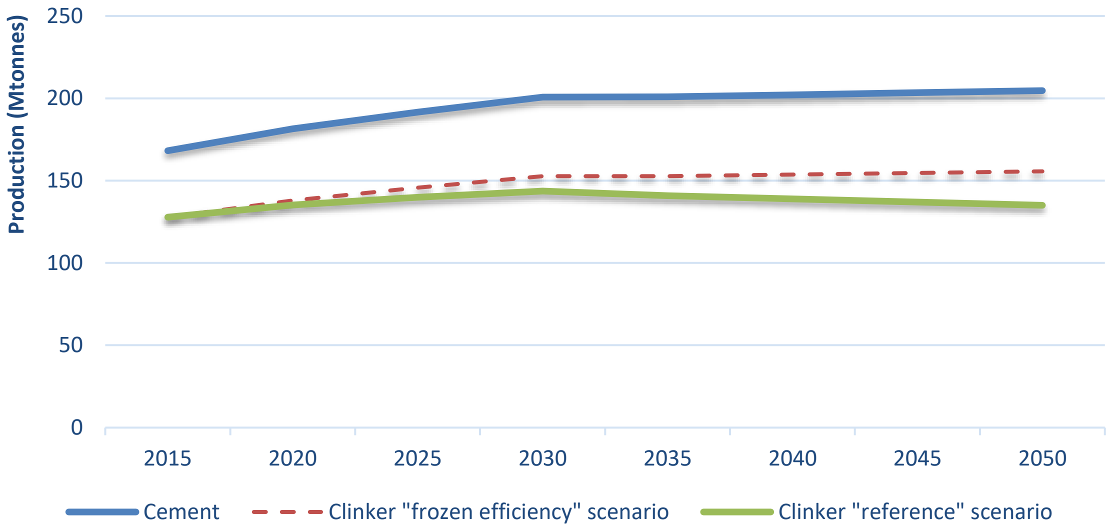

Figure 4 Cement and clinker production in the frozen efficiency and reference scenarios.

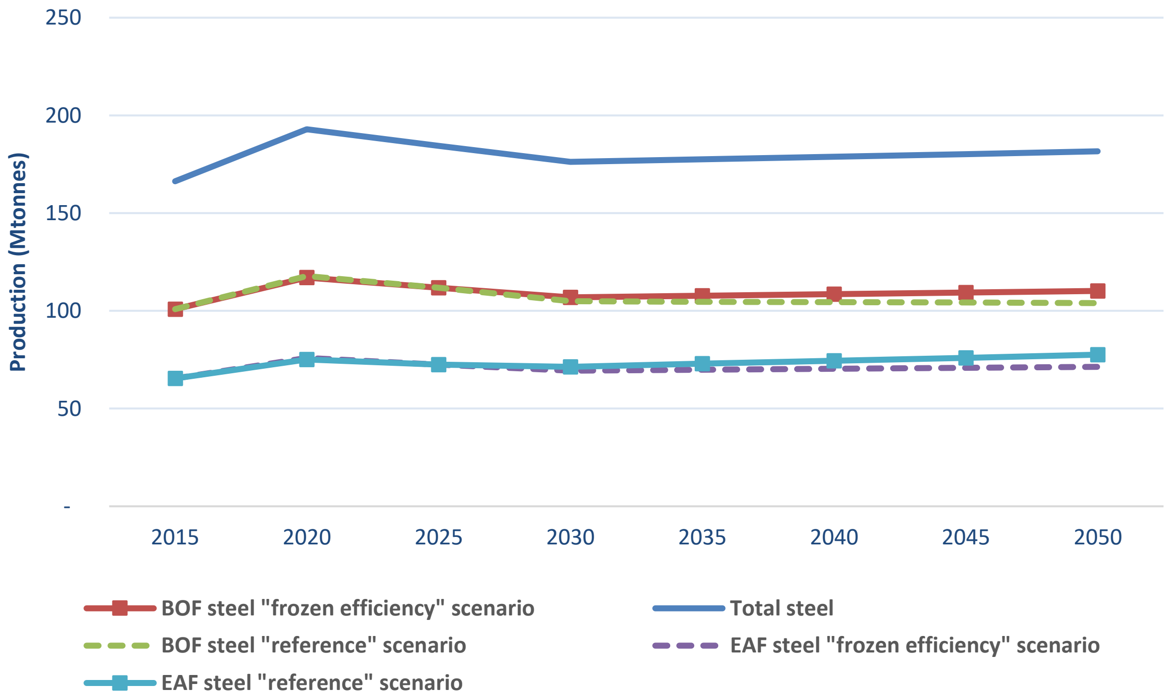

Figure 5 Total steel production and steel production with the BOF and EAF route in the frozen efficiency and the reference scenarios.

Table 4 shows the specific energy consumption for the manufacture of important industrial products and the shares of fuel and electricity used for heating and cooling. The SEC values refer to 2015 and remain constant in the frozen efficiency scenario. Table 5 shows the shares of the energy used either for heating or cooling per different temperature level. In this analysis, and due to the lack of data, we have assumed that the shares for cooling and heating remain fixed in both the reference and the frozen efficiency scenarios.

Table 4 Specific energy consumption (in GJ/tonne) and energy shares for heating and cooling for main industrial products (HRE4; 2017).

Products	Specific energy consumption		Share for Heating		Share for Cooling	
	Fuels	Electricity	Fuels	Electricity	Fuels	Electricity
Chemicals						
Carbon black	52.7[1]	1.8	100%	0%	0%	6%
Ethylene	31.8[1]	0	100%	0%	0%	0%
Methanol	15	0.5	100%	0%	0%	4%
Ammonia	11.3	0.5	100%	0%	0%	6%
Soda ash	11.3	0.3	100%	0%	0%	0%
All rest_chemicals			100%	0%	0%	3%
Iron and Steel						
Blast furnace	11.6	0.6	100%	0%	0%	0%
Rolled steel	1.8[2]	0.4[2]	100%	10%	0%	0%
Electric arc furnace	1	2.3	100%	95%	0%	0%
Coke oven	3.2	0.1	100%	0%	0%	0%
All rest iron and steel			100%	0%	0%	0%
Non-ferrous metals						
Aluminium_primary	0	55.8	100%	5%	0%	0%
All rest non-ferrous metals			100%	5%	0%	0%
Non-metallic minerals						
Cement	3.7[3]	0.5[3]	100%	0%	0%	0%
Flat glass	10.9	3.3	100%	0%	0%	6%
Container glass	5.8	1.4	100%	4%	0%	6%
All rest non-metallic minerals			100%	0%	0%	2%
Pulp and paper						
Paper	5.5	1.9	100%	1%	0%	1%
Chemical pulp	12.7	2.3	100%	1%	0%	0%
All rest pulp and paper			100%	1%	0%	0.5%
Others						
All rest others			100%	5%	0%	15%

[1] Source: Boulamanti and Moya, 2017

[2] Source: IEA, 2007

[3] Gt/tonne clinker. Source: GCCA, 2020

Table 5 Assumptions on the shares of temperature levels for heating and cooling for main industrial products (HRE4, 2018)

	Cooling			Heating			
Products	**<-30°C**	**-30-0°C**	**0-15°C**	**<100°C**	**100-200°C**	**200-500°C**	**>500°C**
Carbon black	20%	30%	50%	0%	0%	0%	100%
Ethylene	15%	50%	35%	0%	0%	0%	100%
Methanol	0%	40%	60%	0%	0%	0%	100%
Ammonia	20%	30%	50%	0%	0%	0%	100%
Soda ash	5%	45%	50%	30%	40%	0%	30%
All rest chemicals	18%	34%	48%	0%	30%	0%	70%
Blast furnace	0%	0%	0%	1%	1%	1%	97%
Rolled steel	0%	0%	0%	0%	0%	0%	100%
Electric arc furnace	0%	0%	0%	1%	0%	0%	99%
Coke oven	0%	0%	0%	0%	0%	0%	100%
All rest iron and steel	0%	0%	0%	0%	0%	4%	95%
Aluminium, primary	-	-	-	0%	-	-	100%
All rest, non-ferrous metals	0%	0%	0%	0%	0%	0%	100%
Cement	-	-	-	0%	-	10%	90%
Flat glass	-	-	100%	2%	21%	43%	34%
Container glass	-	-	100%	2%	19%	19%	60%
All rest, non-metallic minerals	0%	0%	100%	4%	15%	17%	64%
Paper	-	-	100%	5%	88%	5%	2%
Chemical pulp	-	-	-	0%	100%	-	-
All rest, pulp and paper	0%	0%	100%	3%	94%	3%	1%
All rest, others	5%	25%	70%	13%	28%	9%	50%

3.2 The Mitigation scenarios

The adoption of energy efficiency measures, recycling, material efficiency measures, innovative and other carbon mitigation measures such as fuel switching, are exogenous assumptions. In this chapter, we describe, per industrial sub-sector, all the main assumptions undertaken in the construction of the mitigation scenarios. The summary of all assumptions per scenario and industrial sub-sector is listed in Table 6.

In general, first production decreases based on the assumed recycling or material efficiency rates[2], then all energy efficiency measures (BATs) are adopted, then all innovative measures and lastly all fuel switching measures. In this way we first quantify the reduction of the industrial energy demand according to the Energy Efficiency First Principle (EEFP) and then we quantify the impact on energy demand from the innovative technologies that allow for fuel switching.

The full list of the energy efficiency and fuel switching measures can be seen in Appendix A (Tables 8, 9, 10 and 11). For the estimation of the energy savings per measure (fuel, electricity and hydrogen) and the implementation rates we relied on existing literature (references appear in Appendix A) and own calculations.

Iron and steel

The production developments in the BAT scenario are the same with the Frozen Efficiency scenario. In all other scenarios, the steel produced from scrap with the secondary route (EAF route) increases and the steel produced from iron ore with primary route (BF/BOF steel route) decreases. The share of the steel produced with the EAF route is assumed to increase from 39% in 2015 (Worldsteel, 2018) to 67% in 2050 (Fleiter et al., 2019). In addition, coke and pig iron production also decrease with the same annual rates as BF/BOF steel. The energy efficiency measures available for this sector are many and are applied in all scenarios, except for the Frozen Efficiency. Their implementation rates can be seen in Table 8 in Appendix B. Innovative or emerging technology measures, such as coke dry quenching and top gas recycling are implemented only in the Electrification and the Hydrogen scenarios. In the Electrification scenario, iron ore electrolysis (Ulcowin, Ulcolysis) is considered to only have a small implementation rate in 2030 (10%) while by 2050 it fully replaces the primary steel making route (BF/BOF steel). In the Hydrogen scenario, primary steel making is replaced by direct iron reduction by H_2.

Non-metallic minerals

This analysis only assessed into detail the production of cement, container glass and flat glass. The production developments in the BAT scenario are the same with the Frozen Efficiency scenario. In all other scenarios, it is assumed that cement production relies heavier on clinker substituting materials. The assumption has been made the clinker to cement ratio decreases from 76% in 2015 (GCCA, 2020) to 66% in 2050. A wide range of energy efficiency measures has been identified (see Table 8) that are implemented in all scenarios except for the Frozen Efficiency. Main innovative measures identified is the production of cements with only 25% clinker. It is assumed that this measure has an implementation rate of 11% in 2030 and 100% in 2050. In the glass industry, fast response programmes

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[2] We have chosen to first implement recycling and then energy efficiency measures. In this way, the wide implementation of energy efficiency measures is easier to implement in terms of required investment costs as the production of energy intensive products lower due to recycling.

are assumed to be widely diffused by 2050. In the electrification scenario, by 2050 all clinker kilns use the thermal plasma technology and all gas-fired glass melting furnaces are replaced by induction furnaces. In the Hydrogen scenario, it is assumed that by 2050 all kilns are fired with hydrogen.

Non-ferrous metals

The analysis was conducted for the most energy intensive industries such as the production of primary aluminium (excluding alumina refining and anode baking), secondary aluminium and non-ferrous metal castings. For the rest of the non-ferrous metals (e.g. copper) there was limited data on energy efficiency opportunities. The production developments in the BAT scenario are the same with the Frozen Efficiency scenario. It is assumed that under the BAT (high recycling) scenario and all the other mitigations scenarios the share of the secondary aluminium on the total aluminium production increases from 60% in 2015 to 70% by 2050. The efficiency measures identified are implemented in all scenarios except for the Frozen Efficiency. Innovative measures, such as inert anodes and wetted cathodes have only been identified for aluminium smelting. In the electrification scenario, it is assumed that almost all furnaces (90% implementation rate) used in secondary aluminium and metal casting facilities are replaced with induction furnaces. For the Hydrogen scenario we have not included any technologies due to the limited information in literature.

Chemicals

The chemicals industry is a complex industry with many different products. This analysis was performed for a few chemical products for which enough information could be gathered on future energy savings and energy switching technologies. These chemicals are ammonia, ethylene, methanol, soda ash and carbon black. The production developments in the Frozen Efficiency scenario (see Table 3) are the same in all scenarios. No material efficiency measures, or recycling are considered for this sector. The energy efficiency measures are widely adopted in all scenarios except for the Frozen Efficiency. Innovative measures were not identified. Improvements in the compression and separation section with the use of selective membranes is included in the BATs. In the Electrification and Hydrogen scenarios, the assumption is made that the conventional processes to produce ammonia, methanol and ethylene are replaced with the low-carbon processes that utilize H_2 as feedstock. The adoption of these processes also switches a part, or all the fuel used (energy purposes) to electricity (Bazzanella and Ausfelder, 2017). The conventional processes are generating excess heat (4.3 GJ/tonne ammonia, 1.3 GJ/tonne ethylene, and 2.0 GJ/tonne methanol) that in the low-carbon process must be provided otherwise (Bazzanella and Ausfelder, 2017). We assume that in the electrification scenario this heat is provided by electric boilers and in the Hydrogen scenario by H_2 boilers. The assumption here made is that this heat is required at a temperature higher than 300°C, the temperature limit for industrial heat pumps. For soda ash production heat pumps are adopted for the share of the heat needed at less than 500°C and the rest using electric or hydrogen boilers. For carbon black, we have not included technologies for fuel switching due to the limited data availability.

Pulp and paper

This analysis was conducted for the production of chemical pulp, mechanical pulp, recovered fibres, and three types of paper (board and packaging, tissue, and graphic). The production developments in the Frozen Efficiency scenario (see Table 3) are the same in all scenarios. A wide range of energy efficiency measures has been identified (see Table 8) that are implemented in all scenarios except for the Frozen Efficiency. There are several innovative measures included (see Table 9 in Appendix A) with some important being black liquor gasification and enzymatic pre-treatment. In the Electrification scenario high temperature heat pumps are assumed to fully supply by 2050 the heat requirements in the range of 100-200°C in paper and pulp making. Low temperature heat pumps are also assumed to fully cover the heat requirements at a temperature lower than 100°C. In the Hydrogen scenario, heat pumps are not allowed and all heat requirements in this sub-sector are covered by H_2 boilers.

Table 6 Scenario assumptions for the different industrial sub-sectors.

		Iron & steel	Non-metallic minerals	Nonferrous metals	Chemicals	Pulp & paper
No significant transformation	Frozen efficiency	No uptake of energy efficiency. Energy efficiency remains to the 2015 level.				
	Reference scenario	PRIMES assumptions: - BATs; - Incremental material efficiency.				
Mitigation scenarios	BAT	Wide adoption of energy efficiency measures (BATs); no material efficiency				
	BAT high recycling	Wide adoption of energy efficiency measures (BATs); material efficiency:				
		Share of EAF steel increase from 39% to 67%	Clinker to cement ratio decreases from 76% to 66%	Share of secondary aluminium increases from 60% to 70%	-	Share of paper from recovered fibres increases slightly
	Electrification	Wide adoption of BATs; Material efficiency same as in BAT high recycling; Innovative measures; and Electrification measures:				
		DR electrolysis (Ulcowin, Siderwin, Ulcolysis), electric furnaces	Thermal plasma torches (cement); electric melters (glass)	Induction furnaces (aluminium)	Hydrogen used as feedstock (ammonia, ethylene, methanol); Heat pumps and electric boilers for steam generation	Heat pumps and electric boilers for steam generation
	Hydrogen	Wide adoption of BATs; Material efficiency same as in BAT high recycling; Innovative measures; and Hydrogen measures:				
		Hydrogen based direct reduction (H-DR)	-	-	Hydrogen used as feedstock (ammonia, ethylene, methanol); Hydrogen boilers for steam generation	Hydrogen boilers for steam generation

4 Results by scenario

4.1 Final energy demand

In this section, we present the final energy demand projections in the European industrial sector up to 2050 in the frozen efficiency and the reference scenarios (paragraph 4.1.1) and in the mitigation scenarios (paragraph 4.1.2).

4.1.1 Frozen efficiency and reference scenarios

The total final industrial energy demand decreases in the reference scenario, according to EU (2016), from 11.9 EJ in 2015 to 10.6 EJ in 2050. After a short increase in the first five years, it decreases annually by 1% in the 2020-2035 period and by 0.1% in the 2030-2050 period (see Figure 6Figure 6 Final industrial energy demand projections in the reference and the frozen efficiency scenarios.). This is the result of i) energy efficiency improvements and ii) structural changes in the industrial activities which is assumed to move towards less energy intensive and higher value-added products (European Commission, 2016). Without any energy efficiency improvements and with industrial structural changes included, as depicted in the frozen efficiency scenario, the final energy demand would increase to 14.6 EJ by 2050 at an annual growth rate of 0.6%. The increase is more prominent in the 2015-2030 period where the production growth is stronger (see Table 3).

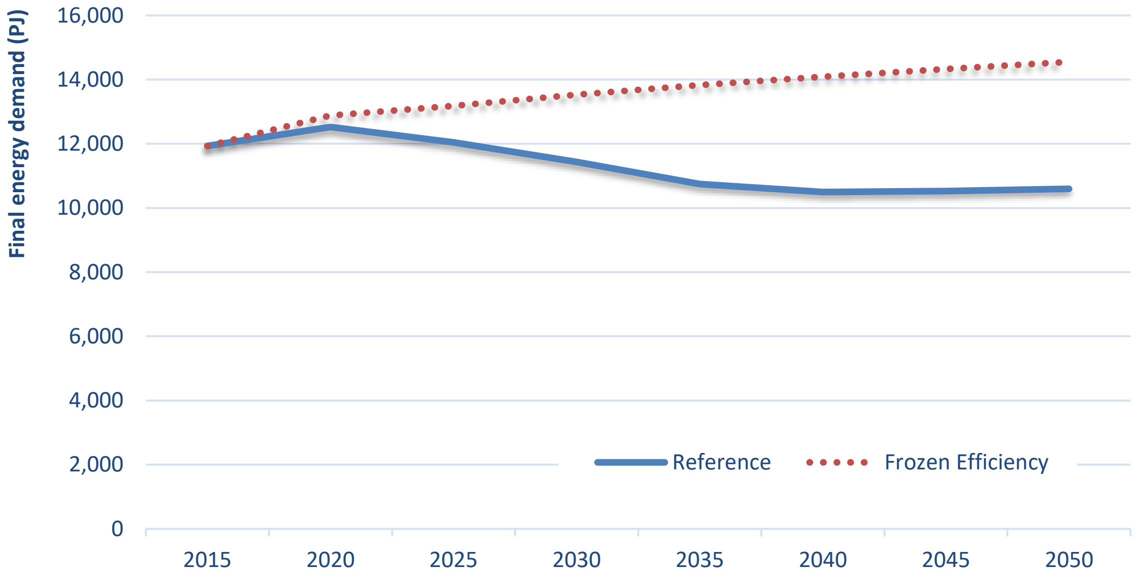

Figure 6 Final industrial energy demand projections in the reference and the frozen efficiency scenarios.

Figure 7 shows the total final energy demand per country in the two scenarios. In 2015, five countries, Germany, France, Italy, UK and Spain were responsible for 59% of the total industrial energy demand in the EU. The same countries are still projected to account for most of the industrial energy use in 2050 (share 57%) in the reference scenario while in the frozen efficiency scenario the share is slightly higher (59%).

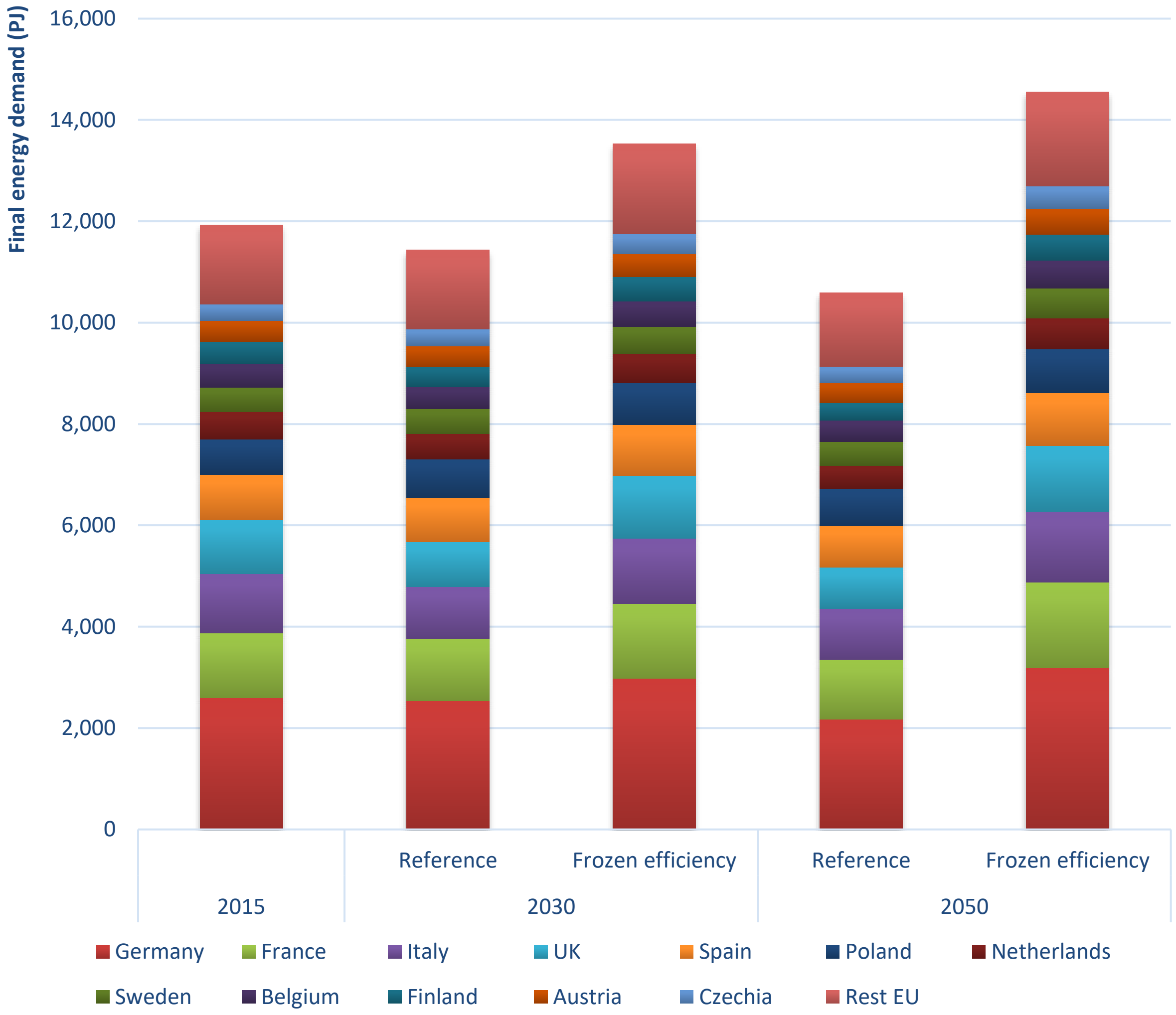

Figure 7 Final industrial energy demand per EU country in the reference and the frozen efficiency scenarios.

Figure 8 shows the developments of main industrial sub-sectors in the EU28 in the period 2015-2050 in the two scenarios. In the reference scenario (0.1% annual decrease in 2015-2050) the sub-sectors that decrease their energy demand are the chemicals (25%), iron and steel (14%), paper and pulp (29%), non-ferrous metals (17%) and non-metallic minerals (15%). The others sector is the only sector increasing its energy demand by about 6%. In the frozen efficiency scenario, where the same structural changes take place as in the reference scenario but no energy efficiency improvements, all sectors increase their final energy demand: chemicals (8%), iron and steel (9%), paper and pulp (10%), non-ferrous metals (8%) and non-metallic minerals (21%) and others (41%).

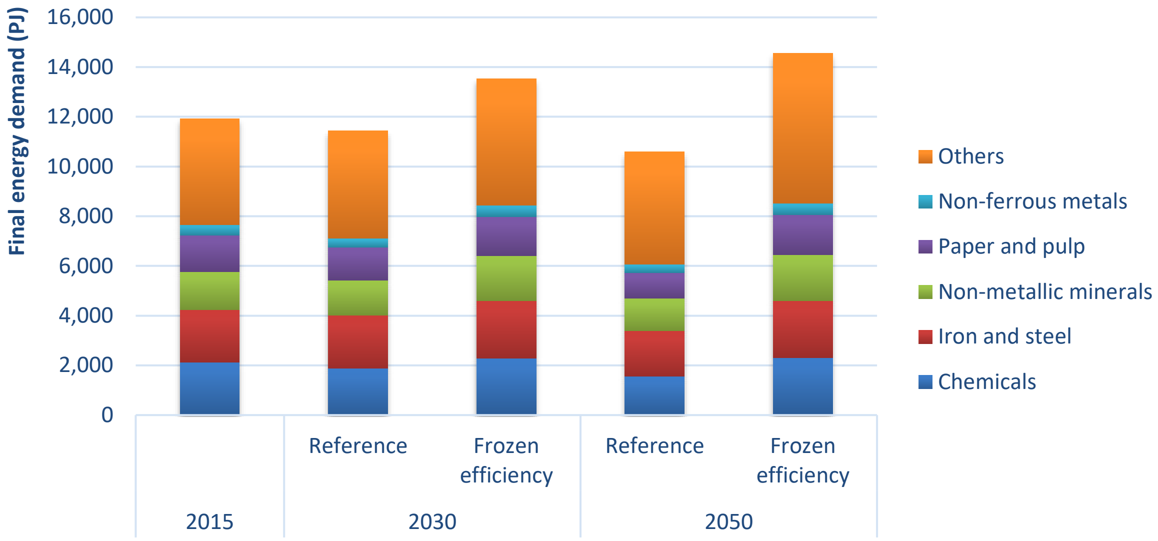

Figure 8 Final industrial energy demand per main industrial sub-sector in the reference and the frozen efficiency scenarios.

The frozen efficiency scenario allows for structural changes (i.e. the switch to higher value added products) but in the iron steel industry it does not allow for i) higher rates of the EAF route than in the base year (2015), and ii) for higher clinker to cement ratios than in the base year. Figure 9 shows the industrial energy demand in the whole industry, and in the iron and steel and the non-metallic minerals industrial sub-sectors when these structural changes are allowed, and they are on the same level with the reference scenario. When these changes are allowed the total final energy demand in the frozen efficiency scenario increases from 11.9 TJ in 2015 to 14.1 TJ in 2050 instead of 14.6 TJ when these changes are not allowed.

Increasing the EAF share from 39% (EU 28 average in 2015) to 43% will reduce the energy demand by approximately 140 PJ in the iron and steel industry. Decreasing the clinker to cement ratio from about 74% (EU 28 average in 2015) to 66% will reduce the 2050 energy demand in the non-metallics minerals sector by about 160 PJ (see Figure 9).

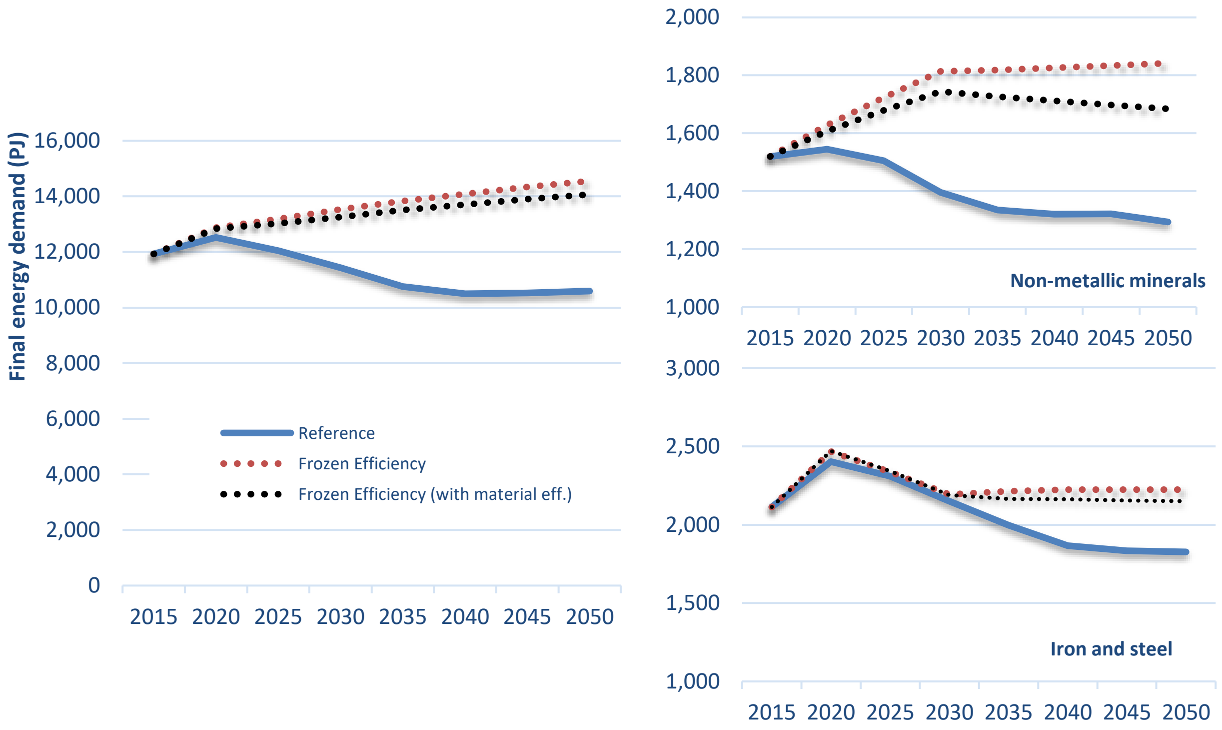

Figure 9 Final energy demand in the EU28 iron and steel and non-metallic minerals industry in the reference and the frozen efficiency scenarios.

Table 7 shows the annual autonomous and policy induced energy efficiency improvement compared to the base year (2015). It is calculated by annualising the difference in the final energy demand (fuel or electricity) between the reference scenario and the frozen efficiency scenario for each industrial sub-sector for the EU28. The highest fuel efficiency improvements in the 2015-2050 period are observed in the pulp and paper, non-ferrous metals and the chemicals industry. It is also observed that the highest rates of improvement are in the period 2020-2035 ranging from 0.00-2.1%. The improvements are lower in the case of electricity, but still the same is observed, i.e. the improvement is stronger in the 2015-2035 period.

Table 7 Annual autonomous and policy induced energy efficiency improvement compared to the base year (2015)

	2020	2025	2030	2035	2040	2045	2050
				Fuel use			
Non-metallic minerals	-0.6%	-1.2%	-1.6%	-1.5%	-1.3%	-1.1%	-1.0%
Iron and steel	-0.7%	-0.4%	-0.4%	-0.7%	-0.9%	-0.9%	-0.8%
Non-ferrous metals	-0.7%	-1.6%	-2.1%	-1.9%	-1.7%	-1.5%	-1.4%
Chemicals	0.0%	-1.1%	-1.6%	-2.1%	-1.9%	-1.6%	-1.4%
Paper and pulp	-0.3%	-1.3%	-1.4%	-1.8%	-1.9%	-1.8%	-1.6%
Others	-0.5%	-1.0%	-1.3%	-1.6%	-1.5%	-1.3%	-1.2%
				Electricity use			
Non-metallic minerals	-1.6%	-0.7%	-0.8%	-0.2%	0.0%	0.1%	0.1%
Iron and steel	-0.6%	0.6%	0.7%	0.7%	0.6%	0.5%	0.5%
Non-ferrous metals	-0.5%	-0.7%	-1.0%	-0.6%	-0.5%	-0.5%	-0.4%
Chemicals	-0.3%	-0.6%	-0.7%	-0.9%	-0.7%	-0.5%	-0.4%
Paper and pulp	-0.3%	-0.3%	-0.3%	-0.4%	-0.5%	-0.5%	-0.4%
Others	-0.6%	-0.4%	-0.5%	-0.4%	-0.3%	-0.2%	-0.1%

Figure 10 shows how the different energy carriers develop in the two scenarios during the 2015-2050 period. In the reference scenario, the share of coal products on the overall energy use decreases from 15% in 2015 to 9% in 2050, for natural gas from 29% to 22%, and for oil from 10% to 6%. The shares of electricity, biofuels and heat increase in the same period from 30%, 9% and 6% to 39%, 15%, and 9%, respectively. Since in the frozen efficiency scenario the shares of the different energy carriers remain stable per sector throughout the analysed period, the energy mix in 2050 is much different than in the reference scenario. Coal accounts for 14%, natural gas for 30%, oil for 11%, biofuels for 9% and electricity for 30%. The shares of biofuel and heat also remain to the 2015 levels.

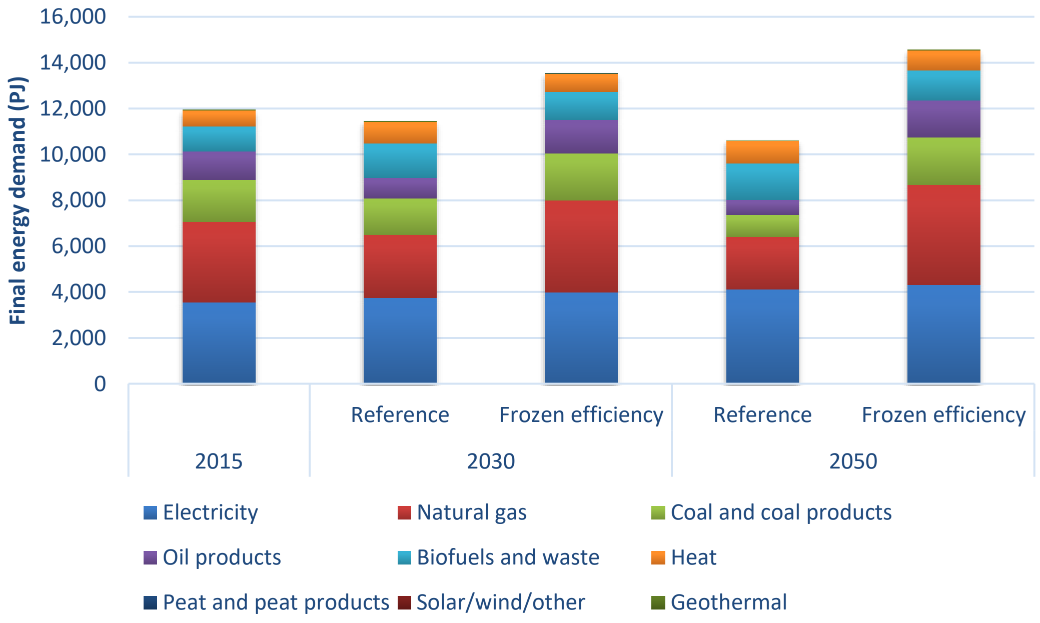

Figure 10 Final industrial energy demand per energy carrier.

Demand for process heating and cooling

Compared to 2015, the demand for heating and cooling in the reference scenario decreases from 8.9 EJ to 7.1 PJ. The shares in total energy demand are reduced from 75% in 2015 to 67% in 2050 in the reference scenario with heat demand being dominant (see Figure 11). Within the 2015-2050 period, the demand for cooling increases by 26% and the demand for heating decreases by 21%. In the frozen efficiency scenario, the demand for cooling increases by 33% and the demand for heating by 22%. This is because the most energy intensive processes with low process cooling needs, such as iron and steel making, decrease their share on the overall final energy demand and because the industrial sub-sectors with higher cooling needs, such as engineering and food industries, increase their share (see all rest Others in Table 4).

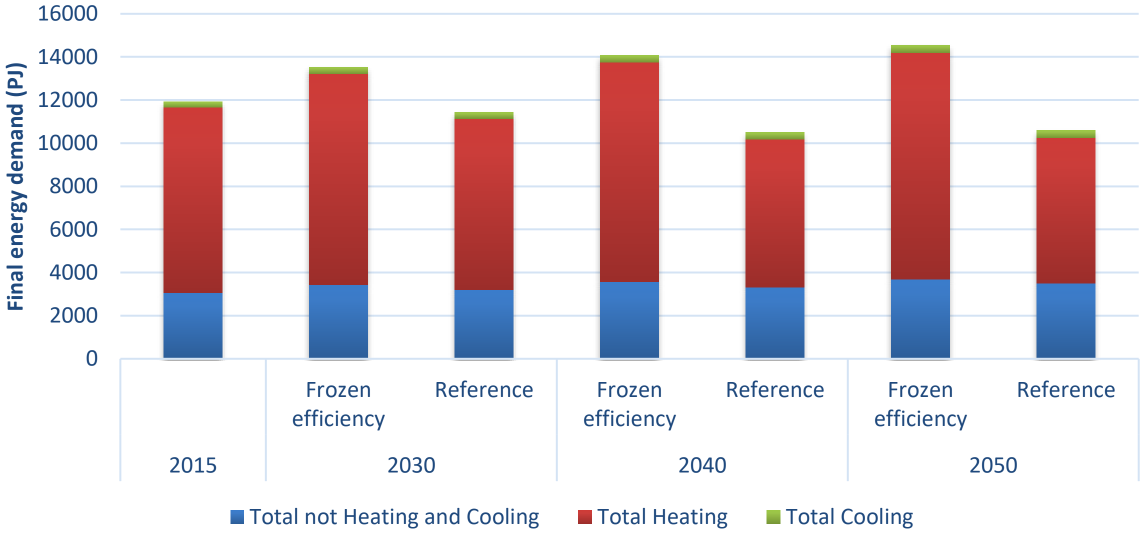

Figure 11 Final energy demand for process heating and cooling and for other purposes (e.g. machine drive) in the reference and the frozen efficiency scenarios.

Most of the heat used is higher temperature heat (>500°C), see Figure 12. One shortcoming of the analysis is that the shares of heating and cooling and the temperatures levels at which these are required, because of the limited data available, are assumed to remain fixed[3]. Figure 13 shows the heating and cooling demand for the countries with the highest industrial energy demand in the reference scenario. The demand for heating is shown to decrease in all countries while the demand for cooling increases.

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[3] Each of the implemented energy efficiency improvement technologies will have an impact on the shares of the heating and/or cooling shares and the temeratures levels. However, because this is difficult to quantify and because no innovative processes are implemented in the reference scenario we make the assumption that the shares remain fixed.

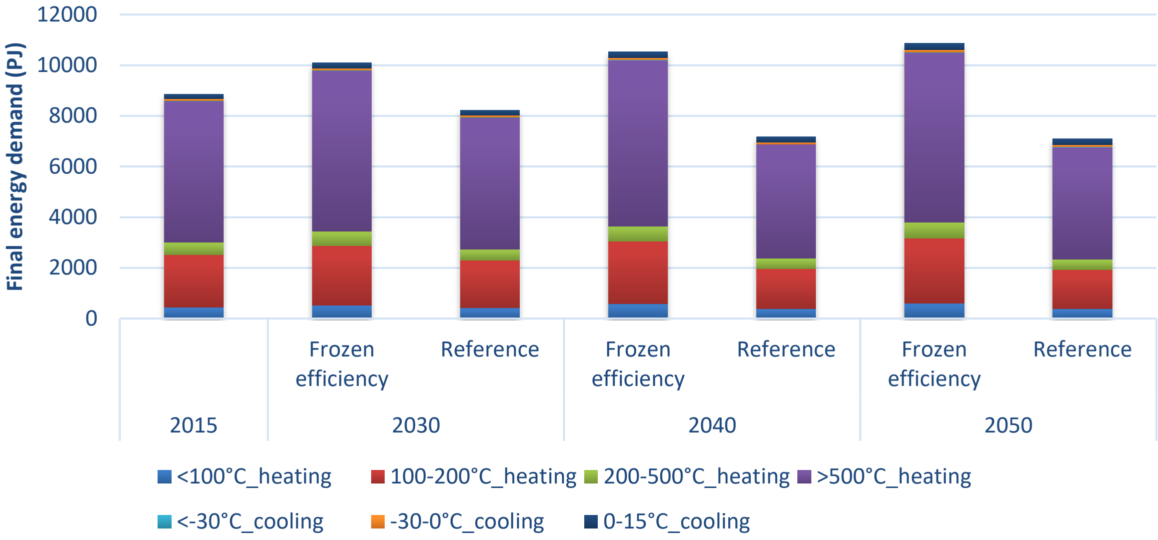


Figure 12 Final energy demand for process heating and cooling per temperature level in the reference and the frozen efficiency scenarios.

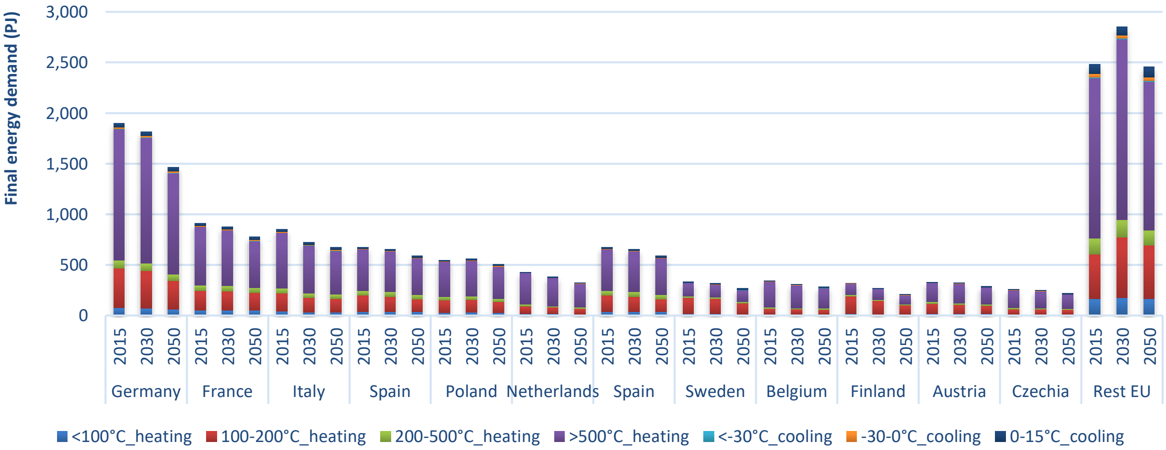


Figure 13 Development of heating and cooling demand in the EU28 by temperature and country in the reference scenario.

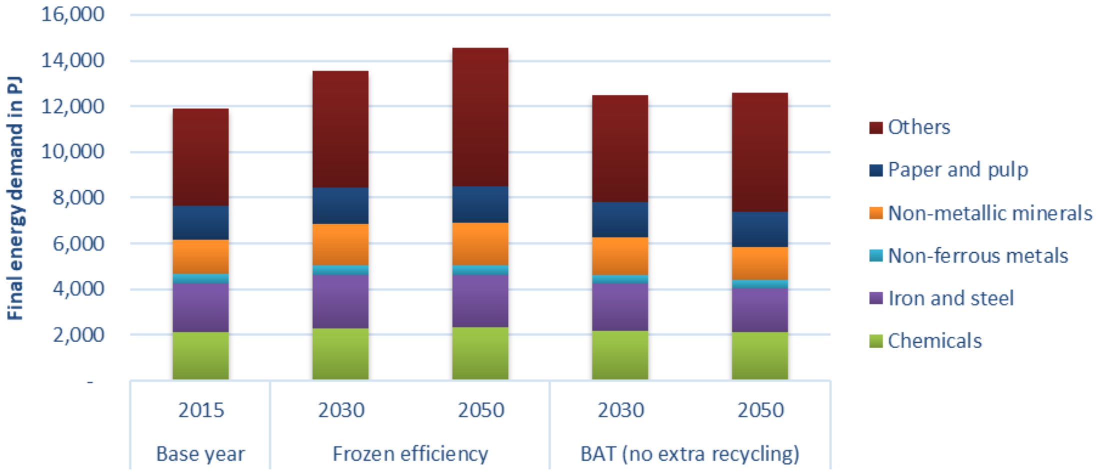
4.1.2 Mitigation scenarios

BAT scenario

The Energy Efficiency scenario, in this report referred to as BAT scenario includes the wide adoption of Best Available Technologies (BATs) across all industries and EU countries. Innovative or emerging technologies are not included. In addition, recycling and material efficiency measures, such as a lower clinker to cement ratio in the cement industry or a higher production of steel from steel scrap are not considered. Recycling levels and clinker to cement ratios in this scenario remain fixed to the same level used in the base year (2015). The production developments in the 2015 to 2050 period remain the same as in the Frozen Efficiency scenario and thereby any changes in energy demand can solely be attributed to the energy efficiency measures.

The BAT scenario results show an increase of the final energy demand by about 6% in 2050 compared to 2015. Without the energy efficiency from the wide implementation of BATs the energy demand in 2050 will be 22% higher compared to 2015. Thereby in 2050, BAT measures can decrease the final energy demand compared to a frozen efficiency scenario by 13.5%. BATs achieve similar savings in fuel and electricity use, calculated at 14% for fuel demand and 13% for electricity demand.

Most savings are achieved in the production of pig iron (163 PJ), cement (133 PJ), rolled steel (67 PJ), EAF steel (42 PJ), ammonia (38 PJ) and ethylene (36 PJ). Detailed energy demand results for the EU28 are listed in Appendix B (Table 12) for each industrial sub-sector and product for 2030 and 2050.



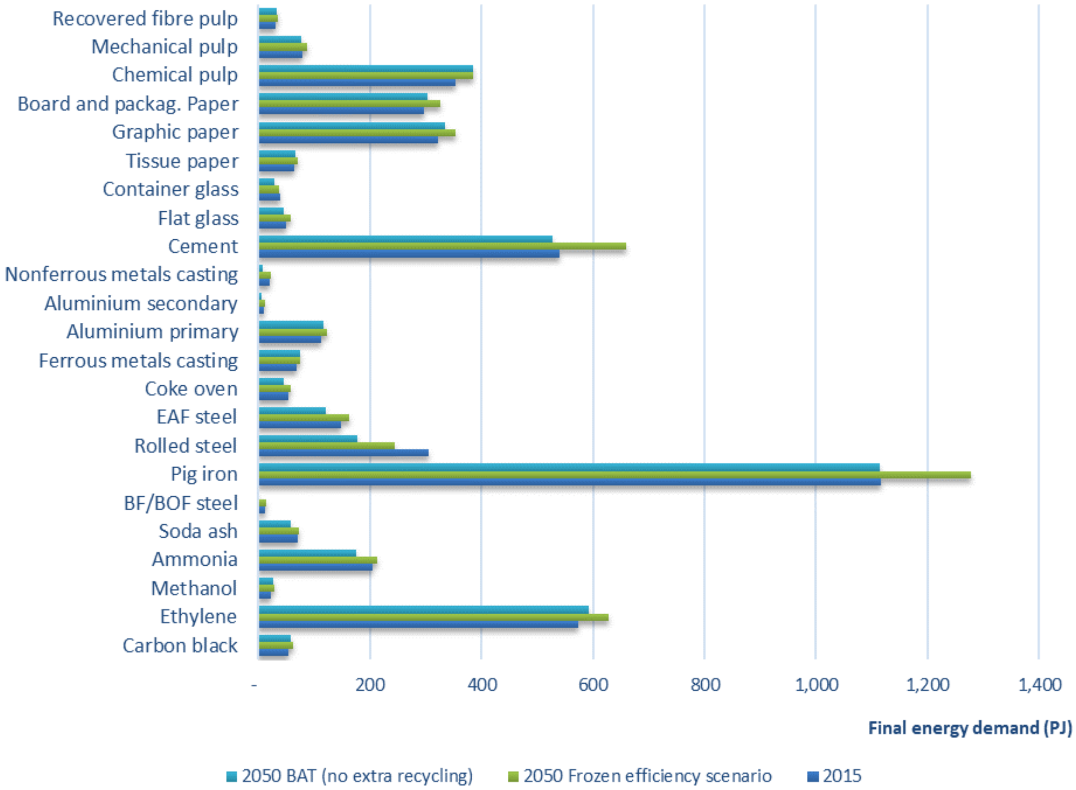


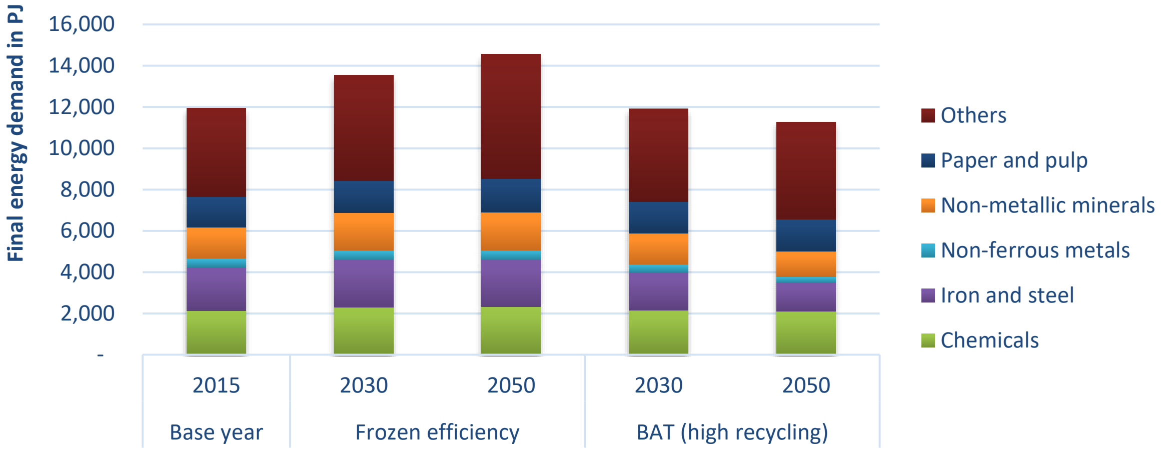
Figure 14 Final energy demand in the BAT (no extra recycling) as compared to the Frozen Efficiency scenario per industrial sub-sector (top Figure) and per industrial product (bottom Figure).

BAT high recycling scenario

The BAT scenario with increased recycling applies all currently available BATs but it also allows for more ambitious levels of material efficiency. It assumes that by 2050 the share of steel produced from scrap has increased considerably, from 39% in 2015 to 67% in 2050, and that the clinker to cement ratio is further reduced, from 76% in 2015 to 66% in 2050. Even so, additional material efficiency efforts such as using less materials when designing a product and material substitution are not included.

The results for the BAT high recycling scenario show a more substantial decrease in final energy demand compared to the BAT scenario described above. In this scenario, the final energy demand decreases considerably by about 6% in 2050 compared to 2015. The 2050 energy demand is 23% lower compared to the Frozen Efficiency scenario. BATs and increased recycling achieve 27% savings in 2050 final fuel demand while the electricity savings are less substantial calculated at 11%.

Most savings are achieved in the production of pig iron (697 PJ), cement (228 PJ), rolled steel (67 PJ), primary aluminium (39 PJ), ammonia (38 PJ) and ethylene (36 PJ). In certain sub-sectors the energy demand increases driven by increased activity as compared to the BAT scenario and the Frozen Efficiency scenarios due to the higher recycling levels. Such an industry is the steel making from scrap industry (EAF steel) where the energy use is 27% higher compared to the Frozen Efficiency scenario. Detailed energy demand results for the EU28 for each industrial sub-sector and product for 2030 and 2050 are listed in Appendix B (Table 13).



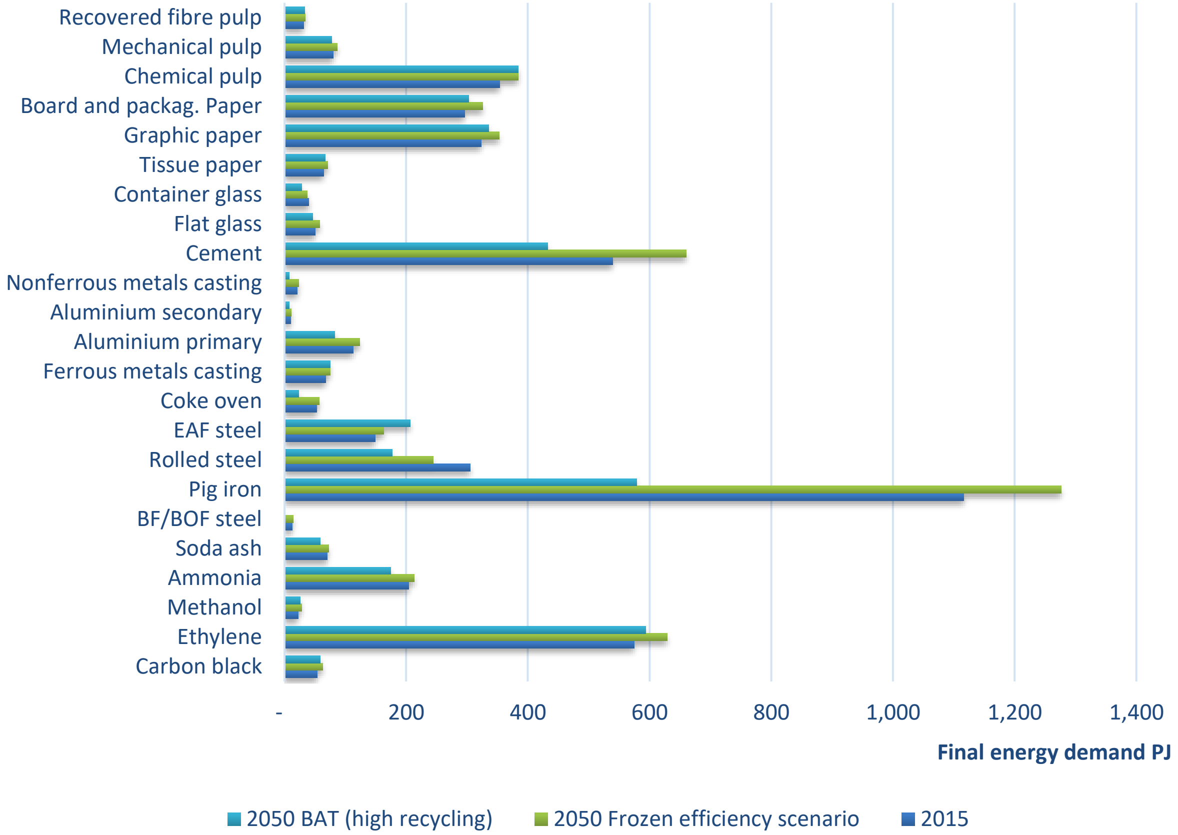


Figure 15 Final energy demand in the BAT (high recycling) as compared to the Frozen Efficiency scenario per industrial sub-sector (top Figure) and per industrial product (bottom Figure).

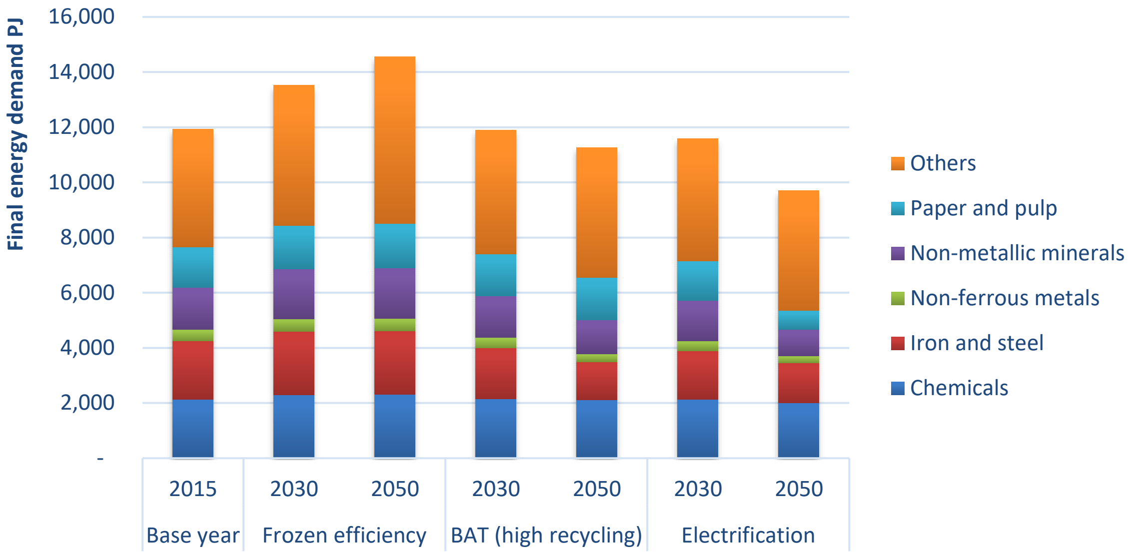
Electrification scenario

In this scenario, the assumptions on production developments, adoption of energy efficiency measures/technologies, increased recycling (e.g., increased EAF steel, secondary aluminium) and material efficiency (i.e., lower clinker to cement ratios) are the same as in the BAT high recycling scenario. However, in this scenario innovative measures that can potentially significantly reduce the energy demand are also adopted. We assume that all innovative measures are adopted first and then follow the electrification measures such as Direct Reduced electrolysis in steel manufacture. This assumption means that first the energy demand is lowered and then the fuel switch to electricity is applied.

The steel industry shifts from blast furnaces to DR electrolysis (e.g. Ulcowin), and cupola furnaces are replaced with induction furnaces. In the aluminium industry, already an electrified industry, only innovative measures such as wetted cathodes and inert anodes offer energy reduction in this scenario. In the non-metallics minerals industry, clinker kilns are electrified, and glass is melted using electric furnaces instead of gas-fired furnaces. In the chemical industry, ammonia, ethylene, and methanol are produced by low carbon processes that use H_2 as feedstock. Except for the fossil fuel reduction for non-energy purposes (feedstocks) these three processes rely more on electricity as opposed to the conventional processes. In the pulp and paper industry, gas or biomass-fired boilers are replaced with industrial heat pumps and electric boilers. For heat temperatures below 200°C, a preference is made for heat pumps.

The final energy demand in 2050 decreases by 14% when compared to the BAT (high recycling) scenario and by 34% when compared to the frozen efficiency scenario. Fuel demand in 2050 decreases by 75% compared to the Frozen Efficiency scenario while electricity demand increases by 65%. Detailed energy demand per sub-sector can be found in Appendix B (

Table 14). H_2 demand for use as feedstock also increases, calculated at 4,200 PJ in 2050[4]. The electricity used for the electrolysis in H_2 production is outside the boundaries of this analysis, however it can be estimated at around 5,600 PJ[5].



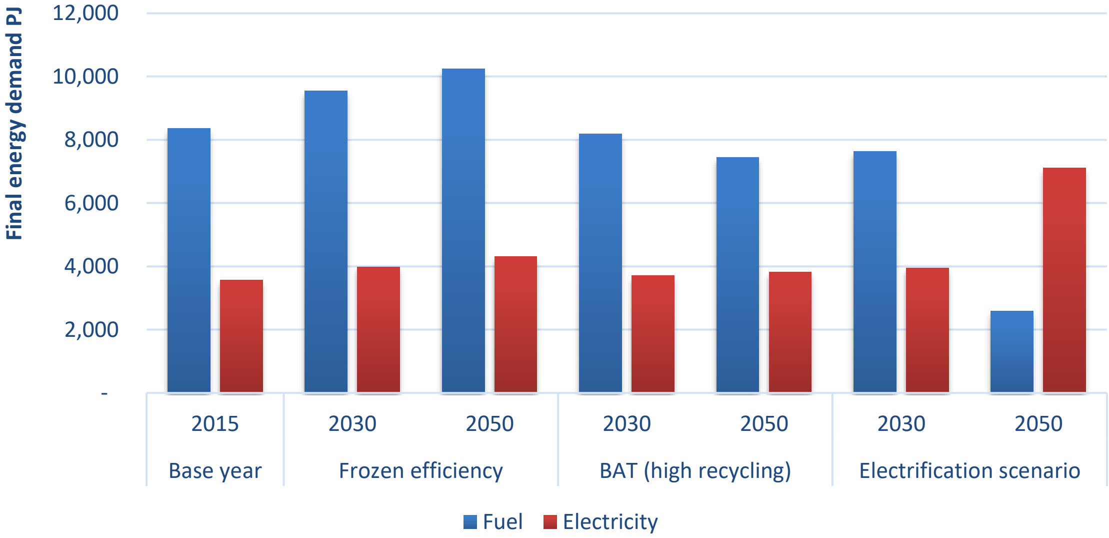


Figure 16 Final energy demand in the Electrification scenario as compared to the other scenarios per industrial sub-sector (top Figure) and per energy carrier (bottom Figure).

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[4] H_2 requirements for feedstock purposes are 178 kg/tonne ammonia, 786 kg/tonne ethylene and 189 kg/tonne methanol (Fleiter et al., 2019). The wide adoption of low carbon processes for these three chemicals will require in 2050 about 18,000 ktonnes of H_2 (energy content of about 4,200 PJ). At the same time, fossil fuel use as feedstock will decrease by about 1,900 PJ.

[5] Estimated based on an electricity consumption for H_2 of about 4.3 kWh/m^3 (Bazzanella et al., 2017).

Hydrogen scenario

In the Hydrogen scenario, technologies that rely on H_2 enter the market and can be widely adopted by 2050. First the energy demand decreases due to the wide deployment of energy efficiency measures, increased recycling and innovative technologies and then the H_2 measures are adopted. In the chemical industry, the conventional processes used in ammonia, ethylene and methanol production are by 2050 entirely replaced by low carbon processes that use H_2 as feedstock. In the iron and steel industry the primary production route for steel making from pig iron in blast furnaces and basic oxygen furnaces (BOFs) is also replaced by the H_2-based direct reduction process (DR-RES). By 2050, all clinker kilns use H_2 burners while the steam requirements in the entire industry are covered by H_2 boilers. In this scenario electrification measures, such as heat pumps and electric boilers, are not included.

The final energy demand in 2050 is 20% lower than in the Frozen Efficiency scenario, 4% higher than in the BAT (high recycling) scenario and 21% higher than in the Electrification scenario. The energy losses in electrolysis for H_2 generation are not included.

The H_2 measures included in this scenario result in a net increase in energy use. For the specific sectors analyzed[6] they offer the potential to decrease the fuel use by about 1,900 PJ while at the same time they increase the electricity use by 680 PJ and the H_2 use (excluding non-energy purposes) by about 1,300 PJ[7]. Another reason for the high calculated final energy demand in this scenario is the assumption made for the Others industry and the "Rest of …" industries (e.g. Rest of iron and steel, Rest of non-metallic minerals) where it is assumed that the fuel consumed for steam generation or heat below the 500°C is provided in this scenario with H_2 boilers (efficiency 95%) while in the Electrification scenario by electric boilers (efficiency 99.9%). In addition, the industrial heat pumps that are assumed to operate on 75% waste heat and 25% electricity (Marsidi, 2018a; 2018b) offer significant savings in the Electrification scenario as compared to the H_2 scenario that are assumed to have a zero-diffusion rate.

Detailed energy demand projections for 2030 and 2050 and per industrial product can be found in Appendix B (Table 15).

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[6] Cement, BF/BOF steel, coke ovens, pig iron, chemical pulp, mechanical pulp, recovered fiber pulp, paper, ammonia, methanol and ethylene.

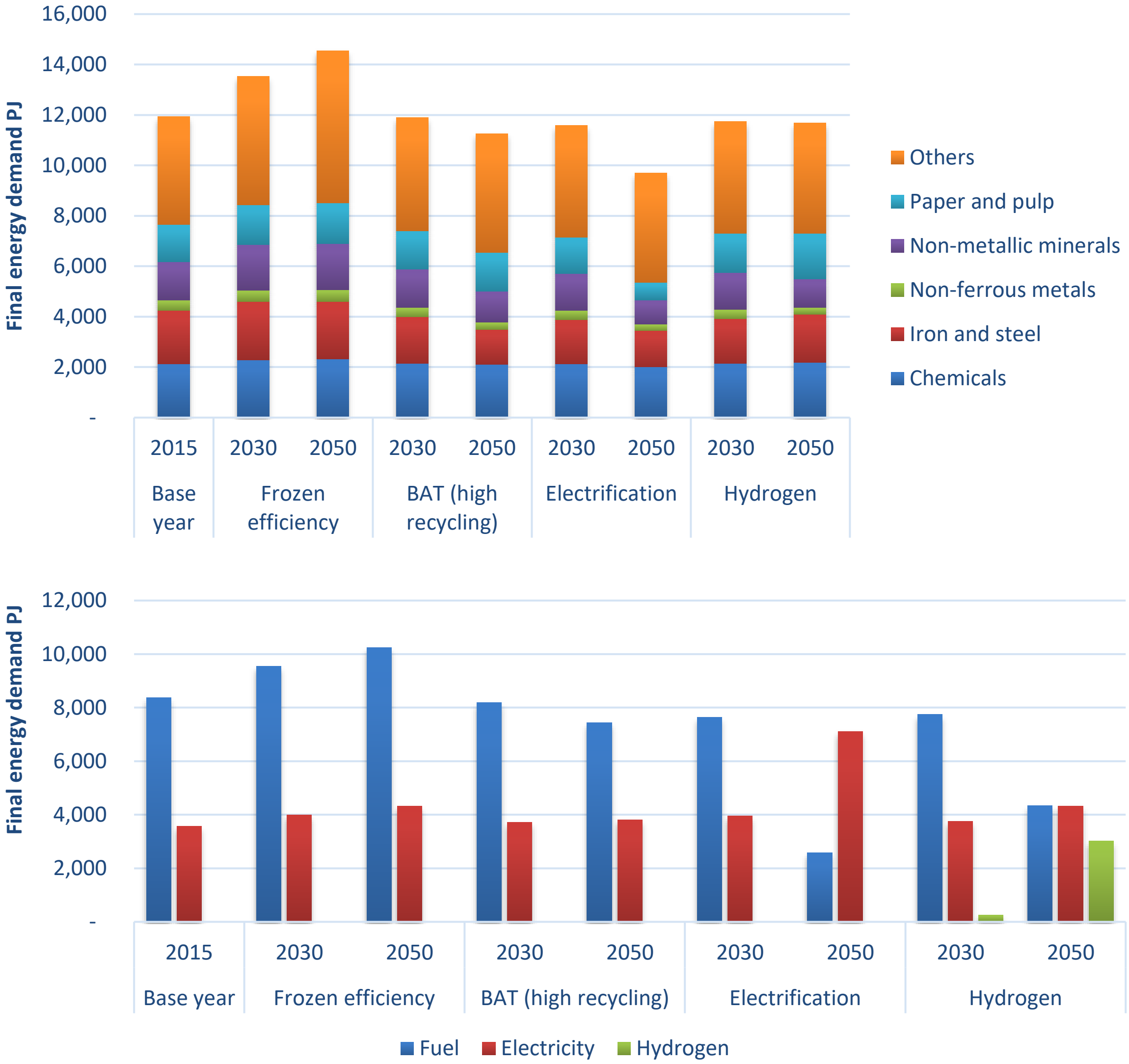

Figure 17 Final energy demand in the Hydrogen scenario as compared to the other scenarios per industrial sub-sector (top Figure) and per energy carrier (bottom Figure).

5 Summary and discussion

Summary of frozen efficiency and reference scenario results

The reference scenario presented in this analysis is based on the EU reference scenario from the European Commission (2016). According to the European Commission (2016) analysis, the industrial energy demand in the EU 28 is expected to slowly decrease from 11.9 EJ in 2015 to reach 10.6 EJ by 2050; with an annual decrease rate of about 0.3%. The uptake of energy efficiency improvements in combination with structural changes are found to over-compensate for the increasing energy demand trends from the growing industrial activities.

By comparing the reference scenario to the constructed frozen efficiency scenario, we calculated the energy savings included in the reference scenario. The frozen efficiency scenario is a variation of the reference scenario that although it considers changes in production developments it assumes no energy efficiency improvements. The comparison reveals that the overall energy savings already included in the reference scenario reaches 27%. Disaggregated per industrial sub-sector this amounts to 35% for the pulp and paper industry, 32% for the chemicals industry, 30% for the non-metallics minerals industry, 24% for the non-ferrous metals industry and 20% for the iron and steel industry.

Summary of mitigation scenario results

In the BAT scenario, it was found that the wide adoption of energy efficiency improvements can reduce the 2050 final energy demand from 14.6 EJ in the frozen efficiency scenario to 12.6 EJ, an energy savings potential of about 14%. Of which, about 200 PJ can be saved in the chemicals industry, 360 PJ in the iron and steel industry and 380 PJ in the non-metallic minerals industry, 110 PJ in the non-ferrous metals industry, 75 PJ in the pulp and paper industry, and around 800 PJ in the Others industry. When increased recycling or material efficiency for three industries (iron and steel, cement, and aluminium) is also considered, the 2050 final energy demand further reduces to 11.3 EJ. This is an energy saving potential of 23% when compared to the frozen efficiency scenario.

We can conclude, when analysing the above scenarios, that the 27% energy savings included in the reference scenario by the European Commission (2016), where energy demand decreases due to BAT implementation and only incremental recycling, is very optimistic. To reach the 2050 final energy demand in the reference scenario, in addition to the wide adoption of BATs, and high recycling levels, more measures such as increased material efficiency and innovative measures will need to be implemented.

The innovative measures identified in this analysis have the potential to decrease the final energy demand by at least another 500 PJ. In the electrification scenario, the final energy demand was calculated to decrease to about 9.7 EJ, an energy savings potential compared to the BAT (high recycling) scenario of approximately 14%. In this scenario, about 73% of the energy demand is covered by electricity and the rest by fuel consumption. In the H_2 scenario, the final energy demand was found to reach 11.7 EJ, 4% higher than the BAT (high recycling) scenario. This is because the H_2 measures included in this scenario result in a net increase in energy use. Also, the use of industrial heat pumps that operate largely on waste heat are in the H_2 scenario not included. In the H_2 scenario, 37% of the final energy demand is covered by fuel consumption, 37% by electricity and 26% by H_2 consumption.

Discussion

The scenarios analysed present possible future developments with industrial activity assumptions on the socio-economic development taken by the European Commission (2016) and as such, they cannot serve as forecasts. In addition to the assumptions made for the future industrial activities, several sets of assumptions have been made with the main ones being:

- For the "Rest of.." sub-sectors, the savings are the average of the sub-sector they belong to and the savings for the Others sector are extrapolated based on the total savings of the sectors for which the detailed analysis was performed. This however might be an underestimation of the BAT savings, since the energy-intensive sectors might already be quite efficient because energy costs are significant. The potential in the Others sector might be higher.
- For these two sectors (Others sector and the "Rest of" sub-sectors), in the electrification and the H_2 scenarios, the savings/energy demand was estimated from the application of electric and electric boilers, respectively, for the share of the energy demand used to provide heat at temperatures below 500°C (see Table 5). The potentials thereby in the Others and the "Rest of …" industries can be higher as also other technologies (e.g. electric furnaces) can be implemented. Currently we account for electrification and H_2 measures for about 82% of the final energy demand.
- In another main simplification, although the diffusion rates for 2015, 2030 and 2050 differ per measure, due to the lack of data we assumed that they are the same for all countries. The same applies for the average energy intensities of the various products manufactured that were assumed to be the same for EU28 countries. However, since we also investigate the energy demand for the manufacture of intermediate products (e.g. clinker used for cement making, coke used in primary steel making, steel from scrap and steel from pig iron) the specific energy intensities per final product differ for the various countries.

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Appendix A

Table 8 Best Available Technologies (BATs) and their implementation rates as compared to the frozen efficiency scenario in 2030 and 2050.

Industrial Sub-sector	Product	Measures/Technologies	Implementation rates	
			2030	2050
Non-metallic minerals	Cement	Improved Raw Mill Blending	40%	70%
	Cement	Use of High-Pressure Roller Presses	40%	70%
	Cement	High Efficiency Classifiers	30%	50%
	Cement	Raw Meal Process Control	30%	50%
	Cement	Energy Management and Control Systems	15%	20%
	Cement	Kiln Combustion System Improvements	5%	5%
	Cement	Indirect Firing	5%	5%
	Cement	Oxygen Enrichment technology	5%	5%
	Cement	Preheater Shell Heat Loss Reduction	5%	5%
	Cement	Conversion to Grate Cooler	15%	20%
	Cement	Optimize Grate Cooler	30%	30%
	Cement	Low-Pressure Drop Suspension Preheaters	20%	25%
	Cement	Heat Recovery for Power Generation (ORC)	58%	100%
	Cement	Increase Preheater Stages (from 5 to 6)	8%	10%
	Cement	Addition of Precalciner or Upgrade	17%	33%
	Cement	Conversion of Long Dry Kiln to Preheater Precalciner	3%	5%
	Cement	Use of Fly Ash, Blast Furnace Slag in Clinker (15% substitution)	2%	92%
	Cement	Biomass and Waste	11%	22%
	Cement	Energy Management and Process Control	20%	20%
	Cement	Replace ball mills with VRMs	35%	68%
	Cement	High-Efficiency Classifiers	30%	30%
	Cement	High efficiency motors	30%	50%
	Cement	Adjustable speed drives	40%	60%
	Container glass	Batch preheating	20%	38%
	Container glass	Increase of cullets	27%	30%
	Container glass	Low Nox burners	21%	37%
	Container glass	Optimized burning	39%	65%
	Container glass	Process Control-Software and Image based control	30%	50%
	Flat glass	Waste heat recovery- el. Generation	5%	25%
	Flat glass	Batch preheating	20%	50%
	Flat glass	Low Nox burners	21%	37%
	Flat glass	Optimized burning_flat glass	41%	66%
	Flat glass	Process Control-Software and Image based control	30%	50%
Iron and steel	Coke oven	Programmed heating in coke oven	50%	70%
	Coke oven	Variable speed drive on coke oven gas compressors	50%	70%
	Coke oven	Coal moisture control	50%	70%
	pig iron	Waste heat recovery blast furnace slag	43%	80%
	pig iron	Top gas recovery turbine	21%	29%
	pig iron	Moisture Removing Blowing Technique in Blast Furnace	65%	75%
	pig iron	Injection of pulverized coal in BF	45%	95%
	pig iron	Cogeneration (for the use of untapped coke oven gas, blast	20%	50%
	pig iron	Recovery of blast furnace gas	3%	5%
	pig iron	Improved hot blast stove control	30%	45%
	pig iron	Improved blast furnace control	25%	50%
	BF/BOF steel	Recovery of BOF and sensible heat	10%	20%
	EAF steel	Scrap preheating	25%	70%
	EAF steel	Converting the furnace operation to ultra-high power (UHP)	45%	70%
	EAF steel	Improving process control in EAF	40%	50%
	Rolled Steel	Recuperative or regenerative burner	30%	36%
	Rolled Steel	Endless Hot Rolling of Steel Sheets	8%	11%
	Rolled Steel	Process control in hot rolling	30%	42%

	pig iron	Variable speed drives for flue gas control, pumps, fans in	15%	15%
	pig iron	Energy monitoring and management systems	25%	50%
Non-ferrous metals	Aluminium primary	PFPB	10%	10%
	Aluminium primary	Optimization electrolysis control	20%	30%
	Aluminium primary	Optimization cell design	20%	30%
	Aluminium	Regenerative or recuperative burner	25%	50%
	Aluminium	New decoating equipment	15%	60%
	Nonferrous metals	Improved process scheduling	39%	40%
	Nonferrous metals	Regenerative or recuperative burner	5%	30%
	Nonferrous metals	Liquid metal as feedstock	20%	45%
Pulp and paper	Mechanical pulp	Heat recovery (TMP, GW)	5%	5%
	Mechanical pulp	Efficient refiner and pretreatment (TMP)	13%	65%
	Recovered fibre	High consistency pulping	25%	40%
	Recovered fibre	Efficient screening	8%	30%
	Recovered fibre	Heat recovery from bleaching	8%	30%
	Recovered fibre	Efficient disperser	22%	30%
	Tissue paper	Efficient refiners	18%	23%
	Tissue paper	Optimization of refining	50%	60%
	Tissue paper	Steambox	2%	5%
	Tissue paper	Shoepress	6%	10%
	Tissue paper	Heat recovery and integration	18%	32%
	Graphic paper	Efficient refiners	18%	23%
	Graphic paper	Optimization of refining	50%	60%
	Graphic paper	Steambox	2%	5%
	Graphic paper	Shoepress	6%	10%
	Graphic paper	Heat recovery and integration	18%	32%
	Board and packag.	Efficient refiners	18%	23%
	Board and packag.	Optimization of refining	50%	60%
	Board and packag.	Steambox	2%	5%
	Board and packag.	Shoepress	6%	10%
	Board and packag.	Heat recovery and integration	18%	32%
Chemicals	Ethylene	Advanced furnace materials	30%	55%
	Ethylene	Improving compression and separation section	18%	28%
	Ethylene	Integration of a gas turbine	12%	15%
	Ethylene	Improved compressors	8%	10%
	Ethylene	Utilization of flare gas	9%	10%
	Ethylene	Modern control system	9%	10%
	Soda ash	Integrated design and operation	25%	40%
	Soda ash	Vertical shaft kiln for the production of concentrated CO2 gas and	20%	30%
	Soda ash	Heat integration	15%	19%
	Soda ash	Modern control system	16%	19%
	Soda ash	Usage of CHP	27%	30%
	Soda ash	Efficiency package	23%	29%
	Soda ash	Usage of more pure feed	27%	30%
	Carbon black	Usage of CHP	10%	10%
	Carbon black	Modern control system	8%	14%
	Carbon black	Optimization of black carbon separation	14%	23%
	Methanol	Efficiency package, synthesis gas section	21%	30%
	Methanol	Efficiency package, methanol synthesis section	27%	37%
	Ammonia	Improved CO2 removal section	20%	31%
	Ammonia	Indirect cooling of the ammonia synthesis reactor	20%	31%
	Ammonia	Increasing the air preheat with waste heat	20%	31%
	Ammonia	Hydrogen recovery (such as PSA)	20%	31%
	Ammonia	pre-reforming	20%	31%
	Ammonia	Advanced process control	30%	55%

Sources used: **Aluminium:** Alsema, 2000; Cusano et al., 2017; HRE, 2018; IPPC, 2005; Kermeli et al., 2015; Moya et al., 2015; Rutten et al. 2017. **Iron and steel:** HRE, 2018; Rutten, et al. 2017; Worrell et al., 2010; Zhang et al., 2014. **Glass:** IIP, 2015; Fleiter et al., 2013; Fleiter et al., 2019; HRE, 2018; Rutten et al., 2017; Scalet et al., 2013; Worrell et al., 2008. **Cement:** Worrell et al., 2013; ECRA, 2017; Zhang et al., 2021; HRE, 2018; Kermeli et al., 2019. **Pulp and paper:** Fleiter et al., 2012; HRE, 2018;

Rutten, et al. 2017. **Chemicals:** Boulamanti and Moya, 2017; HRE, 2018; Moosavi and Tahery, 2014; Neelis et al., 2008; Ren et al., 2006; Worrell et al., 2000; personal communication with Fraunhofer Institute.

Table 9 Innovative measures and their implementation rates as compared to the frozen efficiency scenario in 2030 and 2050.

Industrial Sub-sector	Product	Measures/Technologies	Implementation rates	
			2030	2050
Non-metallic minerals	Cement	Blended Cement (70% BFS)	11%	100%
	Flat glass	Fast response_container glass	18%	48%
	Container glass	Fast response_flat glass	18%	48%
Non-ferrous metals	Aluminium primary	Inert Anodes	5%	90%
	Aluminium primary	Wetted Cathode	5%	90%
	Aluminium primary	Lower the electrolysis temperature	5%	100%
Iron and steel	Rolled steel	Integration of casting and rolling (thin slab strip casting)	39%	45%
	Coke oven	Coke dry quenching	3%	100%
	Pig iron	Top gas recycling	9%	99%
Pulp and paper	Chemical pulp	Black liquor gasification	9%	79%
	Mechanical pulp	Enzymatic pre-treatment	14%	80%
	Tissue paper	Chemical modification	9%	80%
	Graphic paper	Chemical modification	9%	80%
	Board and packag. Paper	Chemical modification	9%	80%
	Tissue paper	New drying techniques	6%	96%
	Graphic paper	New drying techniques	6%	96%
	Board and packag. Paper	New drying techniques	6%	96%
	Mechanical pulp	High efficiency grinding GW	46%	100%
	Recovered fibre pulp	De-Inking flotation optimization	70%	100%

Sources used: **Aluminium:** Moya et al., 2015; Rutten, et al. 2017. **Iron and steel:** HRE, 2018; Rutten, et al. 2017; Worrell et al., 2010; Zhang et al., 2014. **Glass:** Fleiter et al., 2013. **Cement:** Worrell et al. 2013. **Pulp and paper:** Fleiter et al., 2012; HRE, 2018; Rutten, et al. 2017

Table 10 Electrification measures and their implementation rates as compared to the frozen efficiency scenario in 2030 and 2050.

Industrial Sub-sector	Product	Measures/Technologies	Implementation rates	
			2030	2050
Non-metallic minerals	Cement	Thermal plasma torches	0%	80%
	Flat glass	Electric melters	9%	79%
	Container glass	Electric melters	9%	79%
Non-ferrous metals	Aluminium secondary	Induction furnaces	20%	90%
	Nonferrous metals casting	Induction furnaces	20%	90%
Iron and steel	Ferrous metals casting	Cupola to induction	20%	90%
	BF/BOF steel	DR electrolysis (Ulcowin, Siderwin, Ulcolysis)	0%	100%
Pulp and paper	Chemical pulp	Electric boilers	0%	0%
	Chemical pulp	Industrial mechanical vapour recompression (MVR)	0%	0%
	Chemical pulp	High temperature heat pulp	10%	100%
	Mechanical pulp	Electric boilers	0%	0%
	Mechanical pulp	Industrial mechanical vapour recompression (MVR)	0%	0%
	Mechanical pulp	High temperature heat pump	10%	100%
	Recovered fibre pulp	Electric boilers	0%	0%
	Recovered fibre pulp	Industrial mechanical vapour recompression (MVR)	0%	0%
	Recovered fibre pulp	High temperature heat pump	10%	100%
	Tissue paper	Electric boiler	1%	7%
	Tissue paper	Industrial mechanical vapour recompression (MVR)	1%	5%
	Tissue paper	High temperature heat pump	9%	88%
	Board and packag. Paper	Electric boilers	1%	7%
	Board and packag. Paper	Industrial mechanical vapour recompression (MVR)	1%	5%
	Board and packag. Paper	High temperature heat pump	9%	88%
	Graphic paper	Electric boilers	1%	7%
	Graphic paper	Industrial mechanical vapour recompression (MVR)	1%	5%
	Graphic paper	High temperature heat pump	9%	88%
Chemicals	Ammonia	Low carbon ammonia (H_2 as feedstock)	10%	100%
	Ammonia	Electric boilers	10%	100%
	Ammonia	High temperature heat pump	0%	0%
	Ethylene	Low carbon ethylene (H_2 as feedstock)	10%	100%
	Ethylene	Electric boilers	10%	100%
	Ethylene	High temperature heat pump	0%	0%
	Methanol	Low carbon methanol (H_2 as feedstock)	10%	100%
	Methanol	Electric boilers	10%	100%
	Methanol	High temperature heat pump	0%	0%
	Soda ash	Electric boilers	0%	0%
	Soda ash	Industrial mechanical vapour recompression (MVR)	3%	30%
	Soda ash	High temperature heat pump	4%	40%
	Carbon black	Electric boilers	0%	0%
	Carbon black	High temperature heat pump	0%	0%

Sources used: **Aluminium:** Cusano et al., 2017; IPPC, 2005; Moya et al., 2015. **Iron and steel:** IEA/ETSAP, 2010; Keys et al., 2019; Fleiter et al., 2019. **Glass:** Chan et al., 2019; IIP, 2015; Papadogeorgos and Schure, 2019; Worrell et al., 2008. **Cement:** MPA, 2019. **Pulp and paper:** Marsidi, 2018a; Marsidi, 2018b; Marsidi, 2019. **Chemicals**: Bazzanella et al., 2017; Fleiter et al., 2019; Holbrook and Leighty, 2009; Marsidi, 2018a; Marsidi, 2018b; Marsidi, 2019

Table 11 Hydrogen measures and their implementation rates as compared to the frozen efficiency scenario for 2030 and 2050.

Industrial Sub-sector	Product	Measures/Technologies	Implementation rates 2030	Implementation rates 2050
Non-metallic minerals	Cement	Hydrogen	0%	80%
Iron and steel	BF/BOF steel	DR RES H2+EAF	0%	100%
Pulp and paper	Chemical pulp	H_2 boilers	10%	100%
	Mechanical pulp	H_2 boilers	10%	100%
	Recovered fibre pulp	H_2 boilers	10%	100%
	Tissue paper	H_2 boilers	10%	100%
	Board and packag. Paper	H_2 boilers	10%	100%
	Graphic paper	H_2 boilers	10%	100%
Chemicals	Ammonia	Low carbon ammonia (H_2 as feedstock)	10%	100%
	Ammonia	H_2 boilers	10%	100%
	Ethylene	Low carbon ethylene (H_2 as feedstock)	10%	100%
	Ethylene	H_2 boilers	10%	100%
	Methanol	Low carbon methanol (H_2 as feedstock)	10%	100%
	Methanol	H_2 boilers	10%	100%
	Soda ash	H_2 boilers	7%	70%
	Carbon black	H_2 boilers	0%	0%

Sources used: **Iron and steel:** Fleiter et al., 2019; IEA/ETSAP, 2010; Keys et al., 2019; Vogl et al., 2018. **Cement:** MPA, 2019. **Pulp and paper:** Rutten, 2020. **Chemicals**: Bazzanella et al., 2017; Fleiter et al., 2019; Holbrook and Leighty, 2009; Rutten, 2020.

Appendix B

Table 12 Final energy demand in the Frozen Efficiency and the BAT scenarios (Unit: PJ).

Industrial sub-sector	Product	Base year	Frozen efficiency scenario		BAT	
		2015	2030	2050	2030	2050
Chemicals	Carbon black	54	60	63	58	59
	Ethylene	575	620	629	596	594
	Methanol	22	27	28	26	26
	Ammonia	204	213	213	189	175
	Soda ash	70	73	73	63	59
	Rest of chemicals	1,209	1,294	1,309	1,224	1,203
Iron and steel	BF/BOF steel	13	14	14	8	2
	Pig iron	1,117	1,253	1,277	1,165	1,114
	Rolled steel	305	292	244	230	177
	EAF steel	149	158	163	137	121
	Coke oven	53	57	57	49	46
	Ferrous metals casting	68	73	75	73	75
	Rest of iron and steel	408	468	464	427	396
Non-ferrous metals	Aluminium primary	113	122	124	116	116
	Aluminium secondary	11	11	11	9	7
	Nonferrous metals casting	21	23	23	16	8
	Rest of non-ferrous metals	269	291	294	251	207
Non-metallic minerals	Cement	539	648	661	586	528
	Flat glass	51	56	58	50	47
	Container glass	40	42	37	35	28
	Rest of non-metallic minerals	889	1,068	1,086	954	855
Paper and pulp	Tissue paper	65	70	71	68	67
	Graphic paper	323	347	353	337	336
	Board and packag. Paper	296	318	326	305	303
	Chemical pulp	354	374	384	374	384
	Mechanical pulp	80	85	87	82	77
	Recovered fibre pulp	31	33	34	33	33
	Rest of pulp and paper	319	342	356	331	335
Others	Others	4,279	5,100	6,039	4,699	5,206
Total Industry	**Total Industry**	**11,929**	**13,533**	**14,552**	**12,492**	**12,585**

Table 13 Final energy demand in the Frozen Efficiency and the BAT high recycling scenario (Unit: PJ).

Industrial sub-sector	Product	Base year	Frozen efficiency scenario		BAT (high recycling)	
		2015	2030	2050	2030	2050
Chemicals	Carbon black	54	60	63	58	59
	Ethylene	575	620	629	596	594
	Methanol	22	27	28	26	26
	Ammonia	204	213	213	189	175
	Soda ash	70	73	73	63	59
	Rest of chemicals	1,209	1,294	1,309	1,224	1,203
Iron and steel	BF/BOF steel	13	14	14	7	1
	Pig iron	1,117	1,253	1,277	929	579
	Rolled steel	305	292	244	230	177
	EAF steel	149	158	163	173	207
	Coke oven	53	57	57	39	24
	Ferrous metals casting	68	73	75	73	75
	Rest of iron and steel	408	468	464	390	315
Non-ferrous metals	Aluminium primary	113	122	124	103	83
	Aluminium secondary	11	11	11	10	8
	Nonferrous metals casting	21	23	23	16	8
	Rest of non-ferrous metals	269	291	294	245	191
Non-metallic minerals	Cement	539	648	661	537	433
	Flat glass	51	56	58	50	47
	Container glass	40	42	37	35	28
	Rest of non-metallic minerals	889	1,068	1,086	884	722
Paper and pulp	Tissue paper	65	70	71	68	67
	Graphic paper	323	347	353	337	336
	Board and packag. Paper	296	318	326	305	303
	Chemical pulp	354	374	384	374	384
	Mechanical pulp	80	85	87	82	77
	Recovered fibre pulp	31	33	34	33	33
	Rest of pulp and paper	319	342	356	331	335
Others	Others	4,279	5,100	6,039	4,499	4,714
Total Industry	**Total Industry**	**11,929**	**13,533**	**14,552**	**11,904**	**11,263**

Table 14 Final energy demand in the Electrification scenario for 2030 and 2050 (unit: PJ).

Industrial sub-sector	Product	Base year	Frozen efficiency scenario		Electrification	
		2015	2030	2050	2030	2050
Chemicals	Carbon black	54	60	63	58	59
	Ethylene	575	620	629	596	596
	Methanol	22	27	28	24	13
	Ammonia	204	213	213	182	178
	Soda ash	70	73	73	60	27
	Rest of chemicals	1,209	1,294	1,309	1,211	1,134
Iron and steel	BF/BOF steel	13	14	14	7	761
	Pig iron	1,117	1,253	1,277	920	9
	Rolled steel	305	292	244	168	118
	EAF steel	149	158	163	173	207
	Coke oven	53	57	57	38	-0
	Ferrous metals casting	68	73	75	67	45
	Rest of iron and steel	408	468	464	386	299
Non-ferrous metals	Aluminium primary	113	122	124	101	58
	Aluminium secondary	11	11	11	10	8
	Nonferrous metals casting	21	23	23	16	10
	Rest of non-ferrous metals	269	291	294	243	186
Non-metallic minerals	Cement	539	648	661	510	249
	Flat glass	51	56	58	47	29
	Container glass	40	42	37	33	25
	Rest of non-metallic minerals	889	1,068	1,086	870	656
Paper and pulp	Tissue paper	65	70	71	63	22
	Graphic paper	323	347	353	315	121
	Board and packag. Paper	296	318	326	284	101
	Chemical pulp	354	374	384	350	137
	Mechanical pulp	80	85	87	70	34
	Recovered fibre pulp	31	33	34	31	22
	Rest of pulp and paper	319	342	356	321	262
Others	Others	4,279	5,100	6,039	4,438	4,330
Total Industry	**Total Industry**	**11,929**	**13,533**	**14,552**	**11,588**	**9,695**

Table 15 Final energy demand in the Hydrogen scenario for 2030 and 2050 (unit: PJ).

Industrial sub-sector	Product	Base year	Frozen efficiency scenario		Hydrogen	
		2015	2030	2050	2030	2050
Chemicals	Carbon black	54	60	63	58	59
	Ethylene	575	620	629	598	620
	Methanol	22	27	28	25	16
	Ammonia	204	213	213	195	251
	Soda ash	70	73	73	67	REF 91
	Rest of chemicals	1,209	1,294	1,309	1,212	1,141
Iron and steel	BF/BOF steel	13	14	14	7	1,215
	Pig iron	1,117	1,253	1,277	920	9
	Rolled steel	305	292	244	168	118
	EAF steel	149	158	163	173	207
	Coke oven	53	57	57	38	-0
	Ferrous metals casting	68	73	75	73	75
	Rest of iron and steel	408	468	464	386	300
Non-ferrous metals	Aluminium primary	113	122	124	101	58
	Aluminium secondary	11	11	11	10	8
	Nonferrous metals casting	21	23	23	16	8
	Rest of non-ferrous metals	269	291	294	243	183
Non-metallic minerals	Cement	539	648	661	510	408
	Flat glass	51	56	58	49	45
	Container glass	40	42	37	34	25
	Rest of non-metallic minerals	889	1,068	1,086	871	665
Paper and pulp	Tissue paper	65	70	71	70	92
	Graphic paper	323	347	353	350	453
	Board and packag. Paper	296	318	326	315	396
	Chemical pulp	354	374	384	384	492
	Mechanical pulp	80	85	87	71	52
	Recovered fibre pulp	31	33	34	33	39
	Rest of pulp and paper	319	342	356	322	271
Others	Others	4,279	5,100	6,039	4,444	4,387
Total Industry	**Total Industry**	**11,929**	**13,533**	**14,552**	**11,742**	**11,685**