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ORIGINAL ARTICLE

Energy efficiency potentials in the EU industry: impacts of deep decarbonization technologies

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Abstract Increasing the energy efficiency in high energy demand sectors such as industry with a high reliance on coal, oil and natural gas is considered a pivotal step towards reducing greenhouse gas emissions and meeting the Paris Agreement targets. The European Commission published final energy demand projections for industry capturing current policies and market trends up to 2050. This Reference scenario for industry in 2050, however, does not give insights into the extent to which energy efficiency potentials are already implemented, in which sectors further efficiency can be achieved, to what extent or with which technologies. In this paper, the EU Reference scenario is broken down and compared to a Frozen Efficiency scenario with similar GDP developments but without energy efficiency. Through bottom-up analyses, it is found that with energy efficiency technologies alone, this Reference scenario for industry energy demands (10.6 EJ in 2050) cannot be achieved. That means that the EU Reference assumes higher energy efficiency than possible and too high an effect of current policies. In the Frozen Efficiency scenario, the energy demand reaches 14.2 EJ in 2050 due to the GDP development; 22% higher than 2015. Energy efficiency improvements and increased recycling can decrease industrial energy demand by 23% (11.3 EJ in 2050). In order to further reduce the energy demand, our analyses shows that the wide implementation of innovative in combination with electrification or hydrogen technologies can further decrease the 2050 energy demand to 9.7 EJ or 10.3 EJ, respectively.

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Highlights
- In a Frozen Efficiency scenario, the 2050 energy demand in the EU industry increases by 22% compared to 2015.
- The EU Reference scenario for the EU industry is broken down to allow for energy efficiency uptake insights.
- Energy efficiency alone cannot reach the energy savings included in the EU Reference scenario.
- The 2050 industrial energy demand decreases by 23% in an Energy Efficiency plus high recycling scenario.
- The 2050 industrial energy demand decreases by 34% and 29% in a full Electrification and Hydrogen scenario, respectively.

This article is part of the Topical Collection on *Making the Energy Efficiency First Principle Operational*

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Introduction

The industrial sector is the single largest CO_2 emitter in the world. In 2018, the CO_2 emissions released from fuel combusted to drive industrial activities reached 14.4 Gtonnes (Gt), with 54% coming from direct fuel combustion and 46% from indirect fuel combustion for the generation of electricity (International Energy Agency [IEA], 2020). In the same year, the industrial final energy demand reached 164 EJ,[1] 75% of which came from burning fuels and the rest from electricity use (IEA, 2020).

Future material demand is a determining factor for the development of industrial energy demand and related greenhouse gas emissions (GHGs). According to IEA (2019), global steel, cement and aluminium demand is expected to grow in 2060 by 30%, 10% and 75% (compared to 2017), respectively. The World Energy Outlook (WEO) (IEA, 2021) estimates that if current trends continue, total final energy consumption will increase by about 33% (from 156 EJ in 2020 to 207 EJ in 2050). To meet global climate targets and limit the temperature to 1.5 °C, IEA recommends that CO_2 emissions from industrial activities should be 94% below those in 2020, while energy demand can increase moderately by 3% compared to 2020 (IEA, 2021).

Industries in the European Union (EU) are responsible for 9% of global industrial energy demand (13.3 EJ in 2020). To abide by the currently agreed policies, the EU industry will need, in the next 30 years, to limit its energy consumption to 11.7 EJ and in order to meet the climate targets to 9.6 EJ (IEA, 2021). To combat climate change, the EU has put its own climate reduction targets in place. By 2030, GHG emissions should decrease by at least 55% (compared to 1990 levels), the renewable energy share should increase above 32% of the total energy consumption, while energy efficiency should improve by at least 32.5%. In recent plans, an even more optimistic energy efficiency uptake of 36% is proposed (EC, 2020). By 2050, the EU aims to achieve net-zero GHG emissions (EC, 2018a). To achieve the goals, there is a general consensus that a combination of measures will need to be adopted (Åhman et al., 2017; Bataille et al., 2018), from energy efficient technologies to more advanced technologies after 2035, such as Carbon Capture and Storage (CCS), and a switch to CO_2 emission free feedstocks and processes.

Energy efficiency is one of the first steps for climate mitigation (Rosen & Guenther, 2015). This is mainly because energy efficient technologies are readily available and cost-effective, and their adoption tackles several issues from decreasing production costs and increasing the company's comparative advantage to increased energy security and reduced pollution levels (IEA, 2014, 2017; Rosen & Guenther, 2015).

Detailed case studies estimate the potential for energy savings from the wide implementation of energy efficiency measures across several sectors. Chowdhury et al. (2018) identify the energy savings potential of common energy efficiency measures in the UK iron and steel and the food industries to overcome 15%. Owttrim et al. (2022) demonstrate that energy efficiency alone can reduce CO_2 emissions by 66% in the pulp and paper industry. The non-ferrous metals industry in China can reduce its energy use by 20% through energy efficiency (Shao, 2017) while for certain processes, such as alumina refining, the potential is higher than 30% (Kermeli et al., 2015). The bottom-up analysis of energy efficiency measures identified the economic potential for the Swiss cement industry at 14%, while the technical potentials is around 18% (Zuberi & Patel, 2017). The energy savings potentials identified for the UK chemical industry varied per industrial process from 5 to 35% (Griffin et al., 2018). Bottom-up analyses usually focus on a certain industry or manufacturing process, country or the implementation of specific technology types such as waste heat recovery. Other studies, in a more top-down approach, employ benchmarking practices to estimate the energy saving potentials in the various industrial sectors. Although many long-term energy models have a representation of the industry sector, very few have an holistic technology detailed bottom-up approach, such as in Fleiter et al. (2018), with most not representing the industry

[1] Includes the energy use in blast furnaces and coke ovens. The energy use for non-energy purposes, such as feedstock use in the chemical and petrochemical industry (about 36 EJ in 2018), is not included (IEA, 2020).

adequately and modelling the energy and GHG mitigation measures in a rather stylized manner (Edelenbosch et al., 2017).

The EU Reference scenario 2016 (Capros et al., 2016) from the PRIMES long-term energy model makes final energy demand projections per industrial sector and EU country, while capturing current policies and market trends. It includes policies and measures adopted in the EU in 2014 and Directive amendments made in 2015, and it assumes that the availability of EU Emissions Trading System (ETS) allowances faces an annual decrease, following current Directive provisions, and industrial energy efficiency is considered to improve as the result of recent policies such as Ecodesign and labelling and the Energy Efficiency Directive (EED). The EU wide GHG reductions from the Effort Sharing Decision (ESD) are also assumed to be achieved in this scenario. The industrial GHG emission intensity slightly decreases (by 2%) in 2020 (compared to 2010) and decreases more drastically 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 less carbon-intensive fuels (Capros et al., 2016).

However, the EU Reference 2016 scenario does not give insights into the extent to which energy efficiency potentials are implemented and thus, to the extent to which energy efficiency potentials remain untapped in such a baseline scenario in the EU. Obtaining these insights will give valuable information on the pace that energy efficiency needs to be incorporated to reach the climate goals and to what industrial sectors each country should invest in energy efficiency or other measures (if energy efficiency is already achieved).

For this reason, this analysis focuses on constructing a *Frozen Efficiency scenario* that considers the same structural changes as the EU Reference scenario 2016 from PRIMES but with no energy efficiency improvements and recycling uptake. By comparing the final energy demand projections made in these two scenarios, the impact of socio-economic changes and energy efficiency changes on the energy demand projections can be distinguished. In a second step, this study explores four types of alternative future scenarios, able to substantially decrease the final energy demand and/or deeply reduce GHG emissions using detailed bottom-up technological details for the main industrial processes. The developed scenarios have varying degrees of technology diffusion rates and varying types of technological innovations to construct different energy demand pathways for the EU27 + UK industry. All scenarios are based on the Energy Efficiency First Principle (EEFP), meaning that the typical impact on energy use that the use of innovative and fuel switching measures have is adjusted based on the uptake of energy efficiency improvements. For the construction of the different scenarios, no GHG mitigation level is set. The different scenario pathways have been solely developed to identify the technical energy savings potentials under the specific assumptions and to give insights onto the possible impact on energy supply.

The four mitigation scenarios investigated are as follows:

- ***Energy Efficiency scenario***: The energy efficiency scenario assumes that BATs are widely adopted across all industrial sub-sectors.
- ***Energy Efficiency + high recycling scenario***: This scenario has the same assumption as the *Energy Efficiency scenario*, but it also allows for material recycling improvements in main industries (e.g. increased shares of steel production from scrap).
- ***Electrification scenario***: This scenario builds on top of the *Energy Efficiency + high recycling scenario*. It assumes that innovative technologies able to decrease the energy intensity are implemented first and then the technologies that can switch the demand for fuel into electricity.
- ***Hydrogen scenario***: This scenario, builds on top of the *Energy Efficiency + high recycling scenario.* It assumes that innovative technologies able to decrease the energy intensity are implemented first and then the technologies that can switch the demand for fuel into hydrogen.

The article is structured as follows. The "Method" section gives an overview of how the EU Reference scenario 2016 is broken down and the scenario assumptions for the alternative scenario developments. The "Method" section furthermore includes an overview of the main energy efficiency, innovative and fuel switching technologies per main industrial sector. The "Energy demand projections for the

EU industry" section presents the different scenario results for the EU 27 + UK industry, and the "Discussion" section discusses the results and critical assumptions. Finally, the " Conclusions" section presents the main conclusions of the study.

The Supplementary Material (SM) includes detailed data on energy efficiency improving and recycling measures, innovative measures and electrification and H_2 measures used in this analysis.

Method

This section describes the process undergone for constructing the different scenarios.

The starting point is the construction of the baseline scenarios. The two baseline scenarios developed are the (i) *Reference scenario* and the (ii) *Frozen Efficiency scenario*. The *Reference scenario* is the same as the EU Reference scenario 2016 from the European Commission (Capros et al., 2016) where current policies are continued but not tightened albeit with more assumptions about sectoral details. The *Frozen Efficiency scenario* is an alternative baseline scenario that assumes the same socio-economic changes with the *Reference scenario*, i.e. same changes in industrial value added and production volumes, without however allowing for energy efficiency improvements.

In a next step, the mitigation scenarios are developed. In the *Energy Efficiency scenarios*, all technologies/measures that could considerably improve the energy efficiency are considered to be widely implemented, and in the two deep decarbonization scenarios, the *Electrification* and *Hydrogen scenarios*, the main innovative technologies and the electrification and hydrogen technologies are implemented.

The Frozen Efficiency scenario: breaking down the EU Reference scenario 2016

The EU Reference scenario 2016 (Capros et al., 2016) was the most recent scenario at the time of the analysis with data and projections on an EU country and industrial sector level. The reported industrial energy demand includes the 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.

Method

The base year used in this analysis is 2015, the year for which most disaggregated data on energy consumption were available at the time of the analysis.[2] To construct the *Reference* and the *Frozen Efficiency* scenarios, based on the activity levels and base year data used in the EU Reference scenario 2016, the following approach was used (first two steps are made for the *Reference scenario* and the third for the *Frozen Efficiency scenario*):

(i) *The 2015 energy demand reported in the EU Reference scenario 2016 was disaggregated per main industrial sub-sector*. The energy demand in the EU Reference scenario 2016 is reported for five industrial sectors, namely iron and steel, pulp and paper, non-ferrous metals, chemicals, non-metallic minerals and others. The industries included in each sector can be very diverse. For example, the non-ferrous metals industrial sector includes the aluminium, copper and zinc sub-sectors. To assess the different energy efficiency options in detail, the energy demand per main industrial sub-sector needed to be identified. This was done by subtracting the product of the typical EU specific energy consumption (SEC) (in GJ/t) (Fleiter et al., 2017) for each main industrial product and the 2015 activity level from the sectoral energy demand reported in the EU Reference scenario 2016. The remaining energy consumption was assigned to the "Rest of…" of each industrial sector. See Eqs. 1–3.

$$E_{Ref\,j,i,2015} = E_{FrozEff\,j,i,2015} \tag{1}$$

where $E_{Ref\,j,i,2015}$, taken from Capros et al. (2016), is the 2015 energy demand in the Reference scenario of industrial sector j in EU country i, and $E_{FrozEff\,j,i,2015}$ is the energy use in the *Frozen Efficiency scenario*.

The energy use per industrial product ($E_{p_j,i,2015}$) and for the "Rest of…" industries of each sector j ($E_{\text{Rest of j},i,2015}$) was estimated based on Eqs. 2 and 3:

$$E_{p_j,i,2015} = p_{p_j,i} * SEC_{p_j} \tag{2}$$

[2] A check with more recent statistics from data in 2018 has been performed but energy demand projections were similar. We thereby consider that this analysis for the baseline scenarios can still be representative.

$$E_{\text{Rest of j},i,2015} = E_{Ref,j,i,2015} - \sum E_{p_j,i,2015} \quad (3)$$

where $p_{p_j,i}$ is the production of industrial product p of the industrial sector j in country i and SEC_{p_j} is the specifici energy consumption of product p.

ii) The 2015 energy *demand per industrial sub-sector was broken down per energy carrier*. Although the energy carrier breakdown (coal, oil, natural gas, electricity and others) in the EU Reference scenario 2016 is available on a country level, it is not available on an industrial sector level. To disaggregate the industrial energy demand in 2015 per energy carrier (coal, peat, oil, natural gas, electricity, biomass, and waste, geothermal, solar, heat and others) for each industrial sub-sector and country, the IEA (2016a), IEA (2016b) database was used based on Eq. 4.

$$E_{p_j,i,2015,c} = E_{p_j,i,2015} * FS_{c,j,i,2015} \quad (4)$$

where c is the energy carrier and $FS_{c,j,i,2015}$ is its energy share on the overall energy consumption of industry sector j in country i in 2015. The future fuel mix in the *Frozen Efficiency scenario* was assumed to remain the same as in 2015.

iii) *Based on the future activity level from EU (2016), the Frozen Efficiency scenario was constructed.* Based on the *Reference scenario*, a *Frozen Efficiency scenario* was developed where the SEC 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 included 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*. To estimate the future energy demand per sector and country in the *Frozen Efficiency* scenario, the following equations were used:

$$E_{FrozEff,j,i,2050} = \sum E_{FrozenEff,p_j,i,2050} + E_{\text{Rest of j},i,2050} \quad (5)$$

where,

$$E_{FrozenEff,p_j,i,2050} = p_{p_j,i,2050} * SEC_{p_j} \quad (6)$$

$$E_{\text{Rest of j},i,2050} = \sum E_{FrozenEff,p_j,i,2050} * RatioRest_{j,i,2015} \quad (7)$$

where it is assumed that the share of "Rest of…" on the overall energy use of each sector j in each country i ($RatioRest_{j,i,2015}$) remains fixed to the 2015 level.

Data

Table 1 shows the specific energy consumption in the EU for main industrial products.

Table 3 shows the production volumes in 2015 from available statistics and the estimated production developments. The industrial activity projections were estimated based on production data from Capros et al. (2016), Fleiter et al. (2017) and other sources (see Table 2). For the industrial products with limited information on the production developments in the EU Reference scenario 2016, value-added assumptions were used.

Figure 1 shows the industrial value added[3] per industrial sector (Capros et al., 2016). 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 and 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.

Most products experience an increase in production in the 2015–2030 period, while in the 2030–2050 period, most products seem to stabilize (see Table 3). A significant part of the energy-intensive products remains in the EU area (Capros et al., 2016), so there is no expected significant decrease in production.

Table 3 shows the production volumes used for the construction of the *Reference scenario*. 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% (GNR, 2019). In the EU Reference scenario, it is assumed that the potentials for using recycled materials are exhausted (Capros et al., 2016). We thereby

[3] 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 1 Specific energy consumption (in GJ/t) and energy shares for heating and cooling for main industrial products (Fleiter et al., 2017)

Products	Specific energy consumption (SEC) (in GJ/t product)		Share for heating		Share for cooling	
	Fuels	Electricity	Fuels	Electricity	Fuels	Electricity
Chemicals						
Carbon black	52.7[a]	1.8	100%	0%	0%	6%
Ethylene	31.8[a]	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[b]	0.4[b]	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						
Primary aluminium	0	55.8	100%	5%	0%	0%
All rest non-ferrous metals			100%	5%	0%	0%
Non-metallic minerals						
Cement	3.7[c]	0.5[c]	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%

[a]Boulamanti and Moya (2017), [b]IEA, (2007), [c]Gt/tonne clinker (GNR, 2019)

assume that the clinker content in the *Reference scenario* drops to 66%, which is the lowest clinker content used currently in the EU (ECRA/CSI, 2017). In the *Frozen Efficiency scenario*, the clinker content remains stable at 76% (current level).

ii) **The share of steel produced with the electric arc furnace route**. In 2015, the share of steel production 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., 2020). In the *Frozen Efficiency scenario*, we assume that the EAF share remains stable at 39% in the whole period analysed.

The mitigation scenarios

Method

To estimate the energy demand in 2050 in an *Energy Efficiency scenario* for each of the products ($E_{EnergyEff,p_j,i,2050}$), the following equation is used:

Table 2 Summary of main assumptions for projections of industrial activity

Parameters	Sources	Main assumptions for projection
Industrial value added	EU Reference scenario 2016 (Capros et al., 2016)	same as in the EU Reference scenario 2016
Iron and steel	POTEnCIA (Mantzos et al., 2020); (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., 2020);(GNR, 2019); (European Cement Research Academy [ECRA/CSI], 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 Reference scenario 2016 (Capros et al., 2016)	Fertilizers and inorganic chemicals stabilize and slightly decline in later years, methanol, and ethylene experience strong growth
All other industrial products	EU Reference scenario 2016 (Capros et al., 2016); (Fleiter et al., 2017)	No radical changes

$$E_{EnergyEff,p_j,i,2050} = E_{FrozenEff,p_j,i,2050} - P_{p_j,i,2050} * \sum_t Impl.Rate_{t,p_j,2050} * ES_{t,p_j} \quad (8)$$

where $Impl.Rate_{t,p_j,2050}$ is the implementation rate of technology/measure t for the industrial product p_{p_j} in 2050 and $ES_{t,p_j,2050}$ is the typical energy savings potential in GJ/t pf product.

In the other mitigation scenarios, Eq. 9 is used to estimate the energy demand ($E_{DeepMitigation,p_j,i,2050}$). This equation also accounts for energy reductions from implementing energy efficiency measures first.

$$E_{DeepMitigation,p_j,i,2050} = E_{FrozenEff,p_j,i,2050} - P_{p_j,i,2050} * \sum_t Impl.Rate_{t,p_j,2050} * ES_{impr.,t,p_j,2050} \quad (9)$$

$$ES_{impr.,t,p_j,2050} = ES_{t,p_j,2050} - ES_{P_{j,2050}} \Big/ P_{p_j,2050} \quad (10)$$

The $ES_{impr.,t,p_j,2050}$ is the typical energy savings potentials of a certain technology t ($ES_{t,p_j,2050}$) adjusted for the energy savings implemented from the adoption of energy efficient technologies. $ES_{P_{j,2050}}$ are the overall savings from previous measures.

Technology descriptions

The following paragraphs describe the key energy efficiency measures, the key innovative measures and the technologies for the *Electrification* and *H_2 scenarios* for the six most energy-consuming sectors, i.e. cement, chemicals, aluminium, iron and steel, glass and the pulp and paper industries. The full list with all the measures identified and accounted for in this analysis and information on investment costs (in €/t), energy savings potentials (in GJ/t) and current and future diffusion rates are listed in the SM for each of the industrial sectors and main process steps.

The aluminium industry The aluminium industry is composed of the primary aluminium and the secondary aluminium industries. The steps in primary aluminium production are (a) extraction of bauxite, (b) calcination of bauxite into alumina, (c) the smelting of alumina into aluminium and (d) aluminium casting (Green, 2007). The two most energy-consuming steps are aluminium smelting (49 GJ/t) and alumina refining (13 GJ/t) (IAI, 2020).

Almost all smelters in the EU are of the most energy-efficient types, the Point Feed prebake (PFPB) cells, limiting the opportunities for energy reduction from replacing the old and inefficient Söderberg cells (see Table S2 in the SM) (Cusano et al., 2017; Kermeli et al., 2015; Moya et al., 2015). The energy use in EU smelters could be further reduced by improved control systems and improved PFPB cell designs. However, to significantly reduce the industry's energy use, innovative measures, i.e. the use of inert anodes in combination with the wetted cathodes need to be adopted as a retrofit (see Table S8 in the SM). This can reduce the smelting energy use by 3 MWh/t (Moya et al., 2015; Rutten et al., 2017). The alumina refining industry in the EU is small and has not been assessed in this analysis.

Energy use in the secondary aluminium industry, involving facilities where aluminium scrap is re-melted, could be reduced with the use of improved waste heat recovery and new de-coating equipment that limits the requirements for scrap pre-treatment (Moya et al., 2015). Foundries are another area that could achieve significant energy savings with the use of improved waste heat recovery (regenerative burners), better process controls and the use of liquid metal as feedstock (Alsema, 2000).

The aluminium smelting industry is already electrified. To electrify the melting furnaces used in secondary aluminium production and casting facilities, induction furnaces could be used to replace the gas-fired ones (European Commission, 2005).

The cement industry The main steps in cement making are (a) raw material preparation, (b) clinker calcination and (c) cement grinding. Most energy efficiency measures focus on clinker calcination, the most energy-intensive step in cement making (3.6 GJ/t) accounting for 90% of total energy use, and most of which is fuel (Worrell et al., 2013).

There are two main ways to decrease the industry's SEC: (1) by retrofitting with energy-efficient technologies/measures such as measures that improve combustion, and waste heat recovery, e.g. the addition of extra preheater stages and of a precalciner, and (2) by clinker substitution with supplementary materials that reduce the need for calcination (see Table S7 in the SM) (Kermeli et al., 2019; Worrell et al., 2013). In the *Energy Efficiency + high recycling scenario*, it is assumed that cement production relies heavier on clinker substituting materials than in the base year. The assumption has been made that the clinker to cement ratio decreases from 76% in 2015 (GNR, 2019) to 60% in 2050.

The main innovative measure identified is the production of cements with only 25% clinker (Worrell et al., 2013). It is assumed that this measure has an implementation rate of 11% in 2030 and 100% in 2050. Cement making is a high-carbon intensive process. Possible additional deep decarbonization options include the substitution of fuel with biogas, electricity and hydrogen. CCS is another deep decarbonization option for the cement industry but has not been assessed here. Kiln electrification technologies, such as kiln plasma torches and kilns that use microwave energy to provide the heat needed for calcination, are still in the pilot phase (Xavier & Oliveira, 2021). However, it has been concluded that electrification with the plasma burning technique is technically feasible (MPA et al., 2019). Using H_2 to fire cement kilns can be challenging, but some of the combustion issues could be overcome with the use of a biomass-hydrogen mixture (MPA et al., 2019) (see Table S12 in the SM).

The iron and steel industry This industrial sector is comprised of (i) integrated steel mills that produce steel from iron ore and coke in blast furnaces (BF); (ii) secondary steel mills that produce steel from steel scrap in electric arc furnaces (EAFs), pig and/or direct reduced iron (DRI); and (iii) iron and steel foundries that melt metal and use moulds to create the final products (Worrell et al., 2010). Steelmaking from raw materials in the so-called primary route is very energy-intensive, requiring in the EU about 18 GJ/t liquid steel (Remus et al., 2012). Energy use for steelmaking from scrap is significantly less energy-intensive than steel produced in the primary steel production route.

There is a wide variety of energy efficiency measures/technologies identified in literature for all main process steps such as coal moisture control in coke making, low-temperature heat recovery for cogeneration and improved waste heat recovery (Worrell et al., 2010; Zhang et al., 2019) (see Table S3 in the SM). The sector's energy use can also be reduced through increased recycling, by increasing the volumes of steel produced from scrap instead of raw materials. 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., 2020). In the *Frozen Efficiency scenario*, we assume that the EAF share remains stable at 39% in the whole period analysed, while in the *Energy Efficiency + high recycling scenario*, the share increases 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.

Innovative or emerging technology measures, such as coke dry quenching and top gas recycling, are implemented only in the *Electrification* and the *Hydrogen scenarios* (see Table S9 in the SM). 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 steelmaking route (BF/BOF steel). In the *Hydrogen scenario*, primary steelmaking in 2050 is replaced by direct iron reduction by H_2.

The glass industry The glass industry composes a sub-sector of the non-metallic mineral sector. This analysis addressed the two main segments of the EU glass industry, i.e. container glass and flat glass manufacturing. Depending on the glass melting furnace design, the energy consumption can vary from 3 to more than 40 GJ/t (Scalet et al., 2013).

Energy efficiency can be improved through increased levels of cullet and batch preheating, improved burning and advanced controls (Institute for Industrial Productivity (IIP), 2014; Worrell et al., 2008) (see Table S4 in the SM). Fast response programs are only assumed to be widely diffused by 2050 in the *Electrification* and *Hydrogen scenarios*. In the *Electrification scenario*, by 2050, all gas-fired glass melting furnaces are replaced by induction furnaces (see Table S10 in the SM).

The pulp and paper industry This analysis was conducted for the production of chemical pulp, mechanical pulp, recovered fibres, and three types of paper i.e., board and packaging, tissue, and graphic paper. A wide range of energy efficiency measures are available (Fleiter et al., 2012; Harmsen et al., 2018; Rutten et al., 2017) (see Table S5 in the SM), such as improved heat recovery, which is implemented in all scenarios except for the *Frozen Efficiency scenario*. There are several innovative measures such as black liquor gasification and enzymatic pre-treatment that could further reduce the industry's SEC (Rutten et al., 2017). In the *Electrification scenario*, high-temperature heat pumps are assumed to fully replace gas or biomass-fired boilers by 2050 for the heat requirements that are in the range of 100–200 °C. Low-temperature heat pumps are also assumed to fully cover the heat requirements at a temperature lower than 100 °C. In the *Hydrogen scenario*, all heat requirements are assumed to be covered by H_2 boilers (see Table S11 in the SM).

The chemicals industry The chemicals industry is a complex industry generating a variety of products. This analysis was performed for the chemical products for which sufficient information could be gathered on energy savings and investment costs of currently available, innovative and fuel switching technologies. These chemicals are ammonia, ethylene, methanol, soda ash and carbon black. No material efficiency measures or recycling were 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 were however included in the *Energy Efficiency scenario* (see Table S6 in the SM). In the *Electrification* and *Hydrogen scenarios*, the assumption was made that the conventional processes to produce ammonia, methanol and ethylene are replaced with the low-carbon processes that utilize H_2 as feedstock[4] (see Table S13 in the SM). The adoption of these processes also switches a part, or all the fuel used for energy purposes, to electricity (Bazzanella & 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 & Ausfelder, 2017). Here, it was assumed that in the *Electrification scenario* this heat is provided by electric boilers and in the *Hydrogen scenario* by H_2 boilers. Another main assumption 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 the manufacturing of carbon black, we have not included technologies for fuel switching due to the limited data availability.

Scenario assumptions

The summary of all assumptions per scenario and industrial sub-sector is listed in Table 4.

To construct the different scenarios, the implementation of several technologies/measures was assessed, clustered as follows:

[4] In addition to H_2, CO_2 is also needed as feedstock in the low-carbon methanol and ethylene production routes.

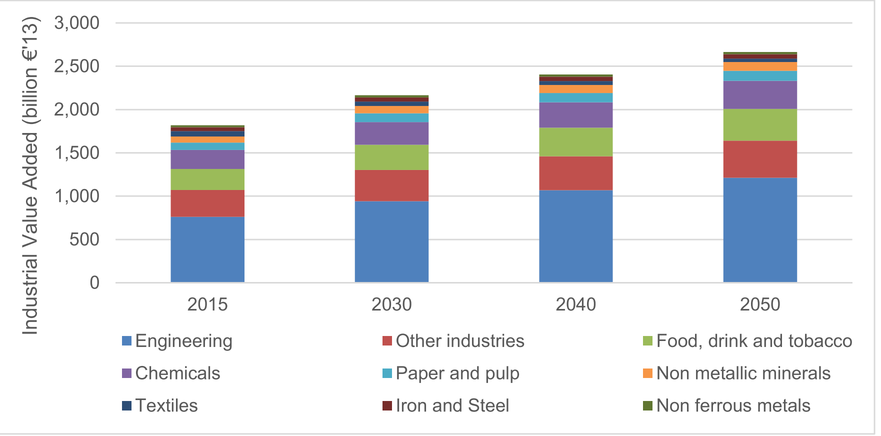

Fig. 1 Industrial value added per industrial sector (Capros et al., 2016)

Table 3 Production developments in the EU27 + UK in the *Reference scenario* (in ktonnes) (Kermeli & Crijns-Graus, 2020)

	2015	2030	25–30%	2040	30–40%	2050	40–50%
Chemicals							
Carbon black	998	1121	12.3%	1143	2.0%	1166	2.0%
Ethylene	16,810	18,091	7.6%	18,398	1.7%	18,306	−0.5%
Methanol	1438	1725	20.0%	1768	2.5%	1812	2.5%
Ammonia	17,394	18,146	4.3%	18,146	0.0%	18,137	0.0%
Soda ash	6025	6323	4.9%	6350	0.4%	6252	−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%
Non-ferrous metals							
Aluminium primary	2242	2422	8.0%	2396	−1.0%	2398	0.1%
Aluminium secondary	3300	3488	5.7%	3447	−1.2%	3438	−0.3%
Non-ferrous metals casting	3672	3972	8.2%	3972	0.0%	3972	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	7175	7762	8.2%	7851	1.1%	7889	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	8236	8712	5.8%	8796	1.0%	8939	1.6%
Recovered fibre pulp	21,294	22,489	5.6%	22,729	1.1%	23,247	2.3%

i) Energy efficiency measures. These are measures that when implemented reduce the energy required per unit of output produced. Examples of energy efficiency measures are waste heat recovery, improved motors, improved insulation etc. All the energy efficiency measures identified are in the form of Best Available Technologies (BATs). Energy efficiency measures that are not currently available are included under the Innovative Measures.

ii) Material efficiency measures. These are measures that lead to a reduction in the amount of primary material needed to provide a specific material service (Worrell et al., 1995). For example, using more steel scrap in steel manufacturing will reduce the need for iron ore, and using more clinker substituting materials in cement making will reduce the need for limestone (Worrell et al., 2017).

iii) Innovative measures. These are technologies that can offer significant energy and GHG reductions compared to conventional technologies but that are currently not available for wide implementation due to the low TRL. They include both energy efficiency measures and material efficiency measures.

iv) Electrification measures. These measures refer to fuel-switching technologies that can replace fossil-fuel based technologies with technologies that use electricity.

v) Hydrogen measures. These measures refer to fuel-switching technologies that can replace fossil-fuel based technologies with technologies that use hydrogen.

Although material efficiency measures and some of the electrification and hydrogen measures can decrease the energy intensity of the process, they are not included under the group of the energy efficiency measures. The adoption of the different measures for each scenario is based on exogenous assumptions.

In general, first production decreases based on the assumed material efficiency rates,[5] then all energy efficiency measures in the form of BATs are adopted, then all innovative measures and lastly all fuel switching measures. In this way, first the reduction of the industrial energy demand is quantified and then the effect of fuel switching on the energy demand.

[5] 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 decreases.

Energy demand projections for the EU industry

This section first presents the *Frozen Efficiency* and *Reference scenarios* in terms of projected final energy demand towards 2050. Then, the developed mitigation scenarios are included for further comparisons.

Frozen Efficiency and Reference scenarios

According to the *Reference scenario*, similar to the EU Reference scenario 2016 (Capros et al., 2016), the industrial energy demand in the EU is shown to decrease from 11.9 EJ in 2015 to 10.6 EJ in 2050. After a short increase in the first 5 years, it decreases annually by 1% in the 2020–2035 period and by 0.1% in the 2030–2050 period (see Fig. 2). This is the result of (i) energy efficiency improvements and (ii) structural changes in the industrial activities which are assumed to move towards less energy-intensive and higher value-added products (Capros et al., 2016).

The constructed *Frozen Efficiency scenario* includes the same industrial structural changes as the *Reference scenario* but without any energy efficiency improvements. The industrial energy demand, without energy efficiency improvements, is found to 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).

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 (57%) in the *Reference scenario*, while in the *Frozen Efficiency scenario*, the share remains the same (59%).

Figure 3 shows the developments of the main industrial sectors in the EU27 + UK in the period 2015–2050 in the two scenarios. In the *Reference scenario* (0.1% annual decrease in 2015–2050), the sectors that decrease their energy demand are 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*, all sectors increase their final energy demand: chemicals (8%), iron and steel (9%), paper and pulp (10%), non-ferrous metals (8%), non-metallic minerals (21%) and Others (41%).

The *Frozen Efficiency scenario* allows for certain structural changes, i.e. the switch to higher value-added products, but it does not allow for (i) higher rates of the EAF route and (ii) higher clinker to cement ratios than in the base year. Figure 4 shows the industrial energy demand in the EU industry when such changes are on the same level as the *Reference scenario*. When these changes are allowed, the energy demand in the *Frozen Efficiency scenario* increases to 14.1 EJ in 2050 instead of 14.6 TJ when these changes are not included.

Increasing the EAF share from 39% (EU 2& + UK 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 76% (EU 27 + UK average in 2015) to 66% will reduce the 2050 energy demand in the non-metallic minerals sector by about 160 PJ (see Fig. 4).

Table 5 shows the annual autonomous and policy-induced energy efficiency improvements compared to the base year (2015). It is calculated by annualizing the difference in the final energy demand (fuel or electricity) between the *Reference scenario* and the *Frozen Efficiency scenario* for each industrial sub-sector. The highest fuel efficiency improvements in the 2015–2050 period are observed in the pulp and paper, non-ferrous metals and chemicals sectors. It is also observed that the highest rates of improvement are in the period 2020–2035 ranging from 0.0 to 2.1%. The improvements are lower in the case of electricity, but still, the same trend is observed, i.e. the improvement is stronger in the 2015–2035 periods relative to the later period.

Figure 5 shows how the different energy carriers develop in the two scenarios (*Reference and Frozen Efficiency*) 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 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 analyzed period, the energy mix in 2050 is different from the *Reference scenario* and does not change much compared to the base year 2015. In 2050, coal accounts for 14%, natural gas for 30%, oil for 11%, biofuels for 9% and electricity for 30%, in the *Frozen Efficiency scenario*. The shares of biofuel and heat remain at the 2015 levels.

Mitigation scenarios

It is found that in the *Energy Efficiency scenario*, the wide adoption of energy efficiency improvements can reduce the industrial energy demand in 2050 from 14.6 EJ in the *Frozen Efficiency scenario* to 12.6 EJ, an energy savings potential of about 14%. About 200 PJ can be saved in the chemicals industry, 360 PJ in the iron and steel industry, 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 is also considered for three industries (iron and steel, cement and aluminium), the 2050 final energy demand further reduces to 11.3 EJ. This is an energy-saving potential of 23%, compared to the *Frozen Efficiency scenario*.

Comparing the *Energy Efficiency + high recycling scenario* to the 27% energy savings obtained in the *Reference scenario*, where energy demand decreases due to BAT implementation and only incremental recycling is allowed, it is evident that the projected energy savings in the *Reference scenario* are very optimistic. In the *Reference scenario*, final energy demand in industry amounts to 10.6 EJ in 2050, which is lower than the final energy demand in the BAT (high recycling) scenario where energy demand reduces to 11.3 EJ. 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 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 *Energy Efficiency + 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 *Hydrogen scenario*, the final energy demand was found to reach 10.3 EJ, 7% higher than the electrification scenario. This is because industrial heat pumps that operate largely on waste heat are not included in the *Hydrogen scenario*. In the *Hydrogen scenario*, 30% of the final energy demand is covered by fuel consumption, 42% by electricity and 29% by H_2.

Table 4 Scenario assumptions for the different industrial sub-sectors for each scenario for 2050

	Scenarios:	Iron & steel	Non-metallic minerals	Non-ferrous metals	Chemicals	Pulp & paper
No significant transformation	*Frozen efficiency*	No uptake of energy efficiency. Energy efficiency remains at the 2015 level.				
	Reference	PRIMES assumptions: - Wide adoption of energy efficiency measures (BATs); - Incremental material efficiency.				
Mitigation scenarios	*Energy Efficiency*	Wide adoption of energy efficiency measures (BATs); No material efficiency.				
	Energy Efficiency+high recycling	Wide adoption of energy efficiency measures (BATs); Material efficiency:				
		Share of EAF steel increase from 39%[a] to 67%[b]	Clinker to cement ratio decreases from 76%[c] to 60%	Share of secondary aluminium increases from 60%[d] to 70%	-	Share of paper from recovered fibres increases slightly
	Electrification	Wide adoption of energy efficiency measures (BATs); Material efficiency same as in the "Energy Efficiency+high recycling" scenario; Wide adoption of innovative measures;				
		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 the "Energy Efficiency+high recycling" scenario; Wide adoption of innovative measures;				
		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

[a]Worldsteel, 2018, [b]Fleiter et al., 2019, [c]GNR, 2019, [d]Statista, 2020; USGS, 2020

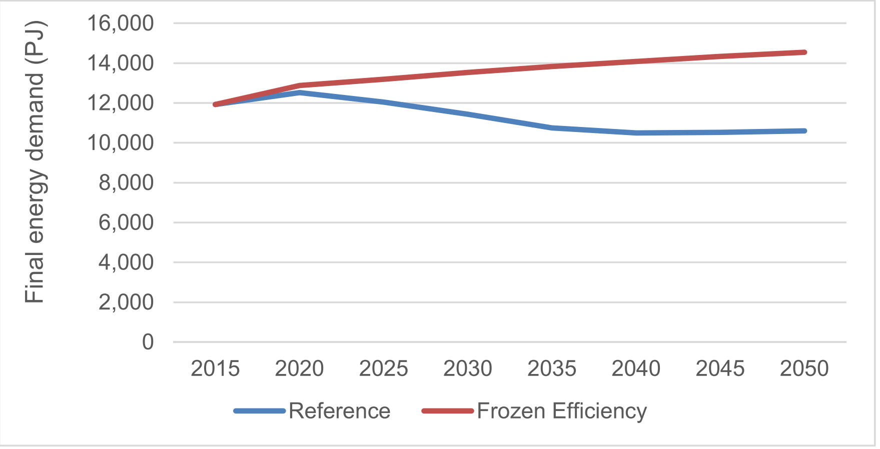

Fig. 2 Final industrial energy demand projections in the *Reference* and the *Frozen Efficiency scenarios*

The energy demand presented in Fig. 6 is final energy demand, i.e. the conversion losses for the production of electricity and H_2 are not included. The degree to which fossil energy savings occur depends on the energy carrier mix used to generate the electricity and H_2.

Impact of EE measures Figure 7 shows the 2050 energy demand under the *electrification* and the H_2 *scenarios* in the cases where (i) material efficiency (incl. recycling) is not included, (ii) material efficiency and innovative measures are not included, and (iii) material efficiency, innovative measures and energy efficiency measures are not included. It can be seen that without the uptake of energy reduction measures the energy demand can be 27% higher in the H_2 scenario and 37% higher in the electrification scenario. In such a scenario, the H_2 demand is 56% higher and the electricity demand 16% higher in the *H_2 scenario*. Also, in the *electrification scenario*, the electricity demand would be 30% higher. Not capturing the full energy savings potential that current and future energy efficiency technologies can offer will result in larger energy demand and significant system energy losses from the production of electricity and H_2 that could be avoided.

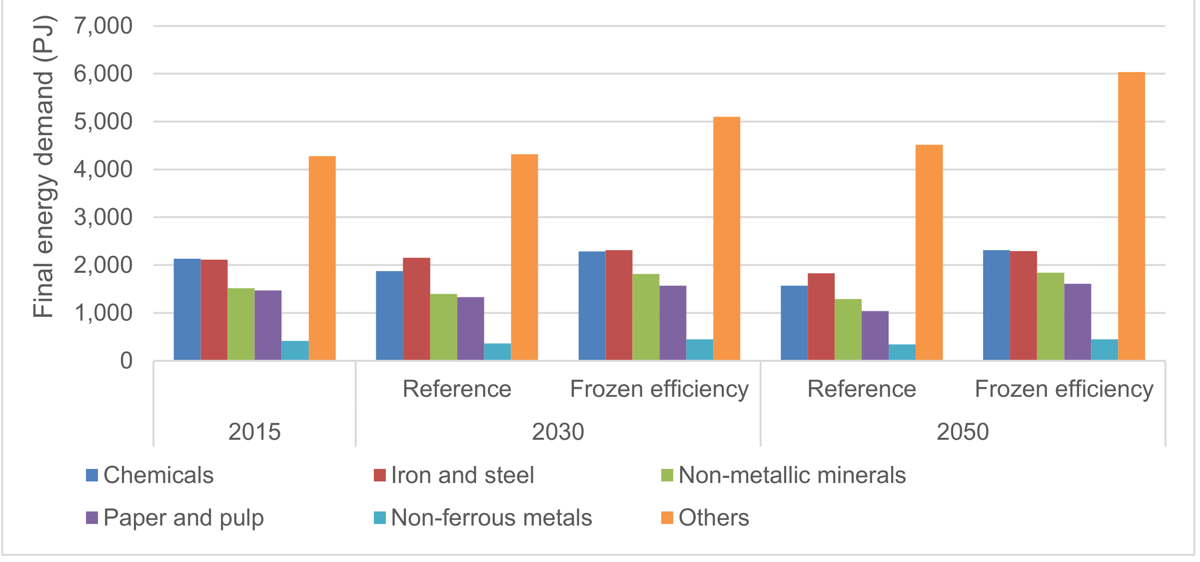

Fig. 3 Final industrial energy demand per main industrial sector in the *Reference* and the *Frozen Efficiency scenarios*

Discussion

The scenarios analyzed present possible future developments while using the industrial activity assumptions on the socio-economic development taken by the EU Reference scenario 2016 (Capros et al., 2016). In addition to the assumptions made for future industrial activities, several sets of assumptions have been made.

The analysis covers the whole EU industrial sector. However, not all industrial sub-sectors have been analyzed in detail. For the "Rest of.." sub-sectors, such as the bricks and clay industries that constitute a part of the non-metallic minerals sector and the copper and zinc industries that are part of the non-ferrous metals sector, the savings are instead assumed to be the average of the sector they belong to. In addition, for the Others sector, the savings are an extrapolation made based on the total savings of the sectors for which the detailed analysis was performed. This however might be an underestimation of the energy savings since the industries analyzed are the most energy-intensive, with high energy costs and might already be quite efficient.

For these two industrial segments, i.e. the Others sector and the "Rest of …" sub-sectors, in the *Electrification* and the *Hydrogen scenarios*, the savings/energy demand was estimated from the application of electric and H_2 boilers, for the share of the energy demand used to provide heat at temperatures below 500 °C (see Table S1 in the SM). Due to the limited information available, no other fuel switching measures were considered. 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. This analysis accounted for electrification and H_2 measures for approximately 82% of total final energy demand.

Another main assumption concerns the implementation rates for 2030 and 2050 and the diffusion rates of the different technologies in 2015. Although

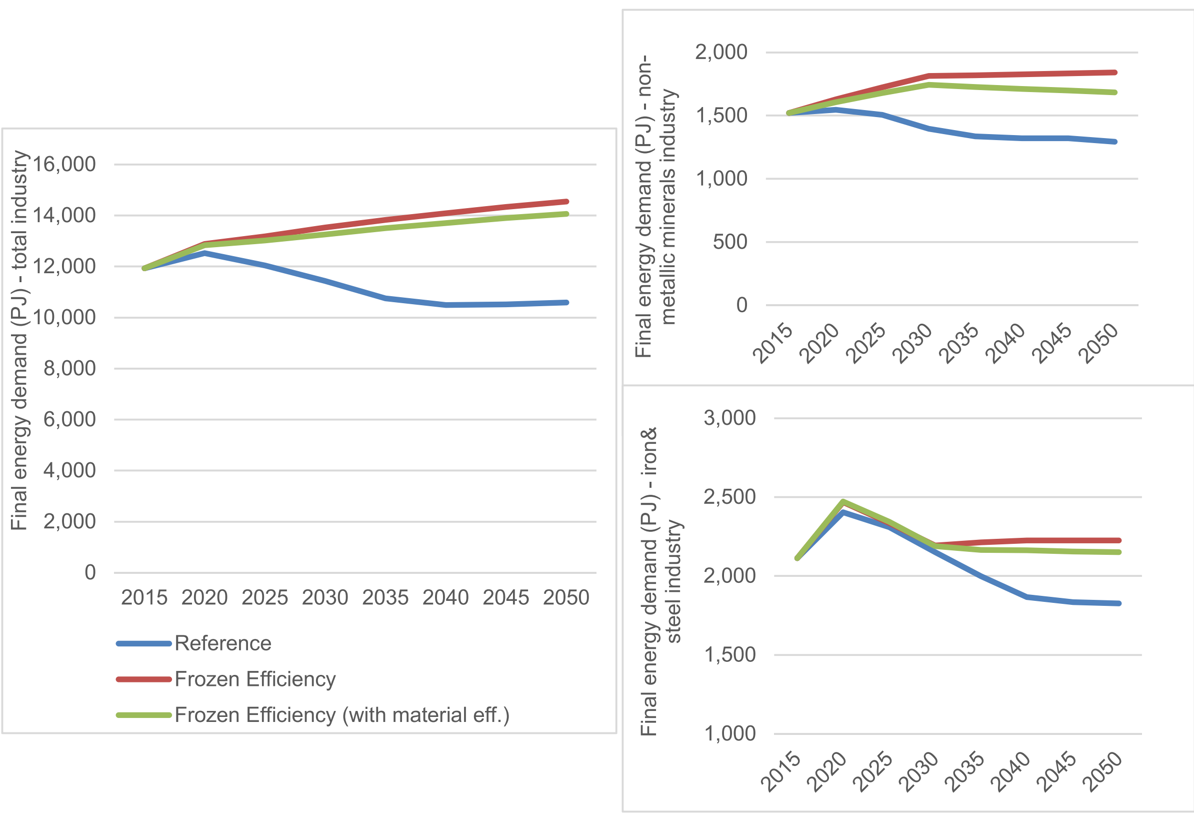

Fig. 4 Final energy demand in the EU27 + UK iron and steel and non-metallic minerals industry in the *Reference* and the *Frozen Efficiency scenarios*

Table 5 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%

the 2015 diffusion rates differ per measure, due to the lack of data, we assumed that they are the same for all countries. The same applies to the average energy intensities of the various products manufactured that were assumed to be the same for all EU27 + UK countries. However, because 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) was also investigated, the specific energy intensities for certain final products differ per country. Although this is an issue for country estimates, it is not for the estimates on an EU level (average EU SEC drops to the BAT or new technology level).

This bottom-up industry analysis was based on the EU Reference 2016 scenario (Capros et al., 2016). A

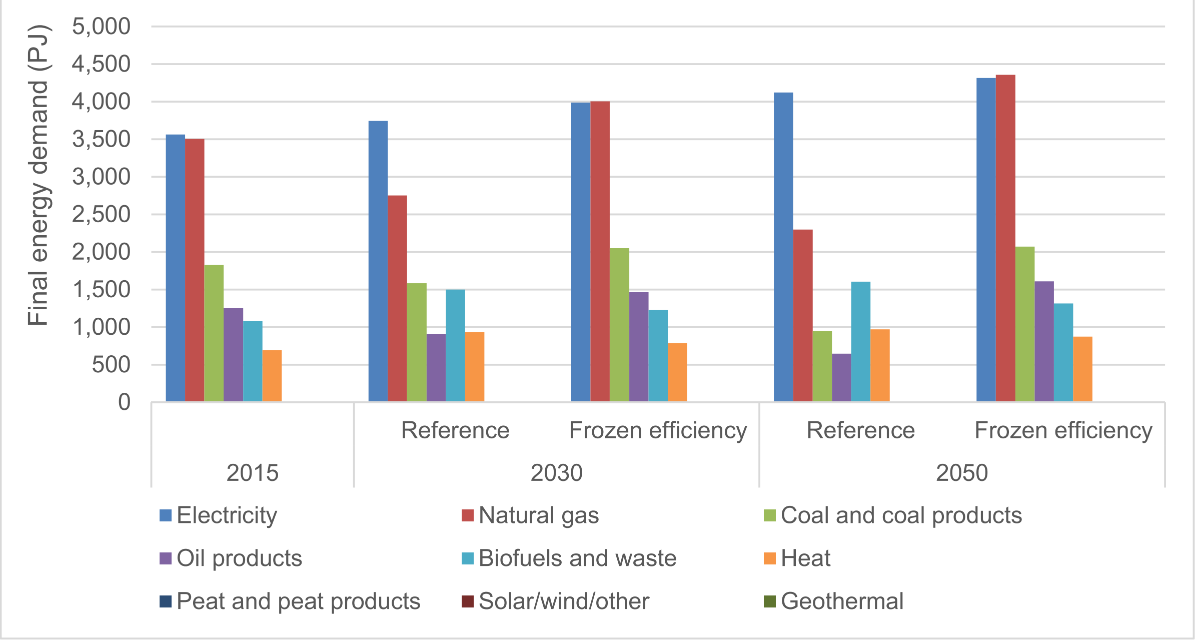

Fig. 5 Final industrial energy demand per energy carrier

check with more recent data from PRIMES 2018, found in European Commission (2018b), revealed that demand projections were similar (2% difference in the 2050 overall demand projections and a similar fuel breakdown). In the latest EU Reference 2020 scenario (Capros et al., 2021), the 2050 industrial energy demand in the EU27 is projected to be 10% lower than in the EU Reference 2016 scenario. The share of natural gas on the overall energy use is slightly higher (27% compared to 24%), while the use of solid fuels is the same (around 9%).

The production developments in the *Frozen Efficiency scenario*, used as the baseline scenario for all mitigation scenarios, were based on the EU Reference scenario 2016. Different production trends would thereby have important impact on the results of this analysis. Overall, the assumptions on production activities made in the EU Reference scenario 2020 for the long term are similar to the 2016 scenario, i.e. the switch to the less energy-intensive industries, the maintained activity in the iron and steel and the non-ferrous metals industry, the increase in the share of engineering on the overall energy use and the stagnation and slight decline of the fertilizers and inorganic chemicals. No information was available on the methanol and ethylene production. Since the projections available in the EU Reference 2020 scenario are not available per industrial sector, a more detailed comparison is hard to perform.

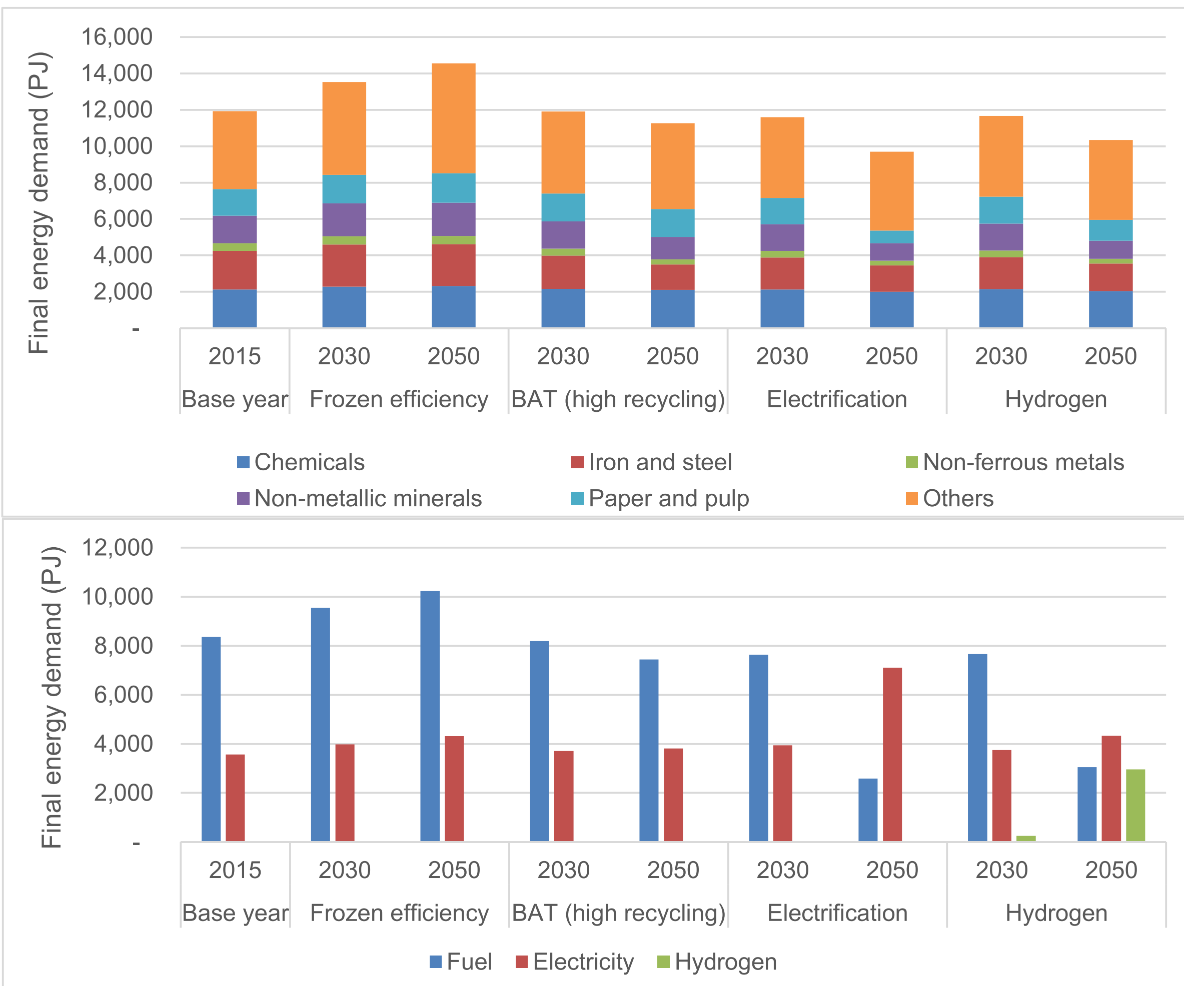

Fig. 6 Final energy demand in the Hydrogen scenario as compared to the other scenarios per industrial sub-sector (top figure) and per energy carrier (bottom figure)

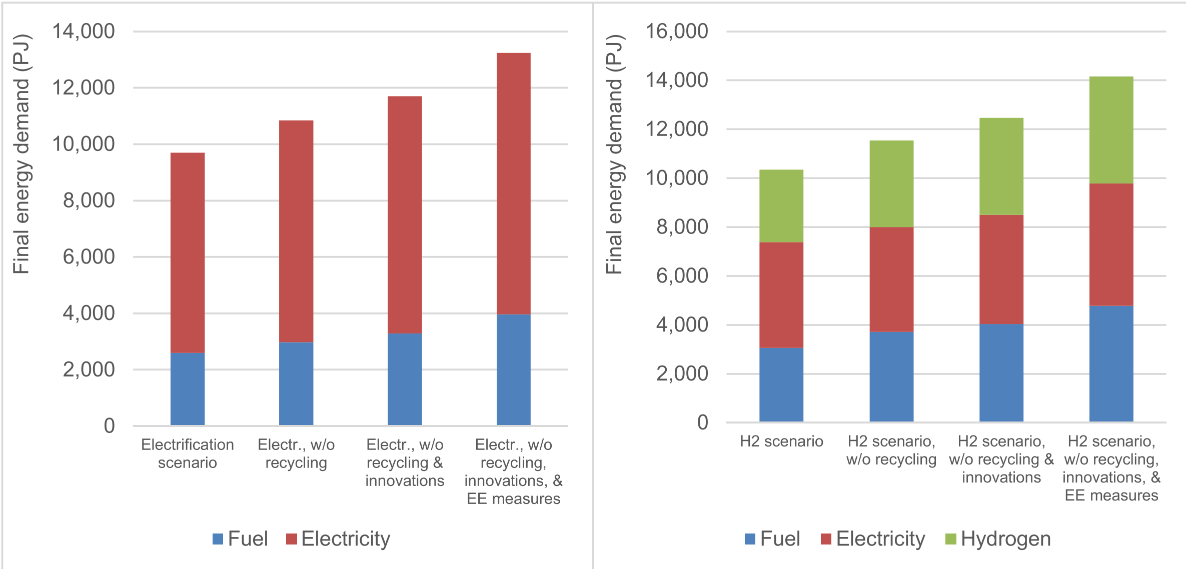

Fig. 7 Final energy demand in the Electrification scenario (left) and the H_2 scenario (right) without the inclusion of measures/technologies that decrease the energy demand

Conclusions

According to the EU Reference scenario developed by Capros et al. (2016), the industrial energy demand in the EU 27 + UK 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%. Although the energy demand is considered to rise in the EU due to the increased level of industrial activities, the uptake of energy efficiency improvements in combination along with the switch of activity from the energy-intensive industries to less energy-intensive industries is found to outweigh the increasing energy demand trends.

In a Frozen Efficiency scenario, the energy demand in 2050 will be 22% higher compared to 2015, reaching about 14.1 EJ. The *Frozen Efficiency scenario* is a variation of the *Reference scenario* that although it considers changes in production developments, no energy efficiency improvements are included. In the *Frozen Efficiency scenario*, industrial energy demand increases at an annual rate of 0.6%. The increase is more prominent in the 2015–2030 period where the production growth is stronger. The energy demand grows stronger in the others (41%) and the non-metallic minerals (21%) sectors, followed by the pulp and paper (10%), iron and steel (9%), chemicals (8%) and the non-ferrous metals (8%) sectors.

The savings already included in the Reference scenario reach 27% of final energy demand in 2050. Disaggregated per industrial sector this amounts to 35% for the pulp and paper industry, 32% for the chemicals industry, 30% for the non-metallic minerals industry, 24% for the non-ferrous metals industry and 20% for the iron and steel industry. Comparing the *Reference scenario* to the constructed *Frozen Efficiency scenario* allowed for the identification of the energy savings already included in the EU Reference scenario 2016.

Energy efficiency improvements alone can decrease the industrial energy demand by 13.5% in 2050. The wide adoption of energy efficiency technologies/measures can reduce the 2050 final energy demand from 14.6 EJ in the *Frozen Efficiency scenario* to 12.6 EJ. 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.

Energy efficiency improvements in combination with increased levels of recycling can decrease industrial fuel use by 27% and electricity use by 11%. When increased recycling or material efficiency for three industries, i.e. iron and steel, cement and aluminium are considered, the 2050 final energy demand further reduces to 11.3 EJ. This is an energy-saving potential of 23% compared to the *Frozen Efficiency scenario*.

Energy efficiency improvements alone cannot reach the savings estimated by PRIMES in the EU Reference scenario 2016. When analysing the above scenarios, the 27% energy savings included in the *Reference scenario* cannot be reached only with increased energy efficiency and an incremental increase in recycling rates. To reach the 2050 final energy demand in the *Reference scenario*, in addition to the wide adoption of energy efficiency measures, high recycling levels, increased material efficiency and innovative measures will need to be implemented.

To decrease the energy demand even further, additional measures are needed. The innovative measures identified in this analysis have the potential to decrease the final energy demand by at least another 500 PJ. In an *Electrification scenario*, the final energy demand in 2050 decreases by 34% and in a *Hydrogen scenario* by 29% when compared to the *Frozen Efficiency scenario*. To achieve these savings, electricity and H_2 will need to be generated by mainly renewable sources. Future research needs to address how the energy efficiency technologies and measures introduced in this study can be combined, and supplemented with further options, to enable a transition to a 100% renewable energy supply in industry. In addition, this assessment could be complemented with the flexibility that the industry sectors could offer, such as with demand response management measures, in an 100% renewable energy system.

Energy and material efficiency measures limit considerably the demand for energy. Without the wide adoption of energy efficiency, material efficiency and innovative energy efficiency measures, the 2050 industrial energy demand is estimated to be 37% and 27% higher, in an *Electrification* and a *Hydrogen scenario*, respectively, compared to when these measures are adopted. Energy efficiency has thereby an important role to play when considering the system integration and optimization for the industrial energy transition.

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Declarations

Conflict of interest The authors declare no competing interests.

References

Åhman, M., Nilsson, L. J., & Johansson, B. (2017). Global climate policy and deep decarbonization of energy-intensive industries. *Climate Policy, 17*(5), 634–649. https://doi.org/10.1080/14693062.2016.1167009

Alsema, E. A. (2000). *A database of energy reduction options for the Netherlands, 1995–2020. Sector study for the Non-Ferrous Metals Industry* [Report nr. NWS-E-2000–08]. Department of Science, Technology and Society, Utrecht University. https://www.semanticscholar.org/paper/ICARUS-4-%3Aa-database-of-energy-reduction-options-%3A-Alsema/fe9914486df216bc250d98b66526f64f42b6fb4f

Bataille, C., Åhman, M., Neuhoff, K., Nilsson, L. J., Fischedick, M., Lechtenböhmer, S., Solano-Rodriquez, B., Denis-Ryan, A., Stiebert, S., Waisman, H., Sartor, O., & Rahbar, S. (2018). A review of technology and policy deep decarbonization pathway options for making energy-intensive industry production consistent with the Paris Agreement. *Journal of Cleaner Production, 187*, 960–973. https://doi.org/10.1016/j.jclepro.2018.03.107

Bazzanella, A. M., & Ausfelder, F. (2017). *Low carbon energy and feedstock for the European chemical industry*. The European Chemical Industry Council (CEFIC). https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_Europen_chemical_industry.pdf

Boulamanti, A., & Moya, J. A. (2017). *Energy efficiency and GHG emissions_Prospective scenarios for the Chemical and petrochemical industry.* Publications Office of the European Union. https://data.europa.eu/doi/10.2760/20486

Capros, P., De Vita, A., Florou, A., & et al. (2021). *EU reference scenario - Energy, transport and GHG emissions: Trends to 2050*. Publications Office of the European Union. https://data.europa.eu/doi/10.2833/35750

Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., Evangelopoulou, S., Zampara, M., Papadopopoulos, D., Paroussos, L., Fragiadakis, K., & Tsani, S. (2016). *EU reference scenario - Energy, transport and GHG emissions: Trends to 2050*. https://data.europa.eu/doi/10.2833/001137

Chowdhury, J. I., Hu, Y., Haltas, I., Balta-Ozkan, N., Matthew, G., Jr., & Varga, L. (2018). Reducing industrial energy demand in the UK: A review of energy efficiency technologies and energy saving potential in selected sectors. *Renewable and Sustainable Energy Reviews, 94*, 1153–1178. https://doi.org/10.1016/j.rser.2018.06.040

Cusano, G., Gonzalo, M. R., Farrell, F., Remus, R., Roudier, S., & Sancho, L. D. (2017). *Best Available Techniques (BAT) Reference document for the non-ferrous metals industries*. Industrial Emissions Directive 2010/75/EU (Integrated Pollution Prevention and Control), Publications Office of the European Union. https://data.europa.eu/doi/10.2760/8224

Edelenbosch, O. Y., Kermeli, K., Crijns-Graus, W., Worrell, E., Bibas, R., Fais, B., Fujimori, S., Kyle, P., Sano, F., & van Vuuren, D. P. (2017). Comparing projections of industrial energy demand and greenhouse gas emissions in long-term energy models. *Energy, 122*, 701–710. https://doi.org/10.1016/j.energy.2017.01.017

European Cement Research Academy. (2017). Development of state of the art-techniques in cement manufacturing: Trying to look ahead. In:C. S. I. (CSI) (Ed.).*World Business Council of Sustainable Development*. http://docs.wbcsd.org/2017/06/CSI_ECRA_Technology_Papers_2017.pdf

European Commission. (2018a). *A Clean Planet for all, A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52018aDC0773. Accessed Sept 2021

European Commission. (2018b). *In-depth analysis in support of the Commission communication COM(2018b) 773 - A Clean Planet for all - A European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*. European Commission. https://climate.ec.europa.eu/system/files/2018-11/com_2018_733_analysis_in_support_en.pdf

European Commission. (2020). *Climate target plan impact assessment. Stepping up Europe's 2030 climate ambition.* https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020SC0176. *Accessed Sept 2021*

European Commission, E. (2005). *Reference document on Best Available Techniques in the smitheries and foundries industry*. Publications Office of the European Union. https://eippcb.jrc.ec.europa.eu/sites/default/files/2019-11/sf_bref_0505_1.pdf

Fleiter, T., Elsland, R., Herbst, A., Manz, P., Popovski, E., Rehfeldt, M., Reiter, U., Catenazzi, G., Jakob, M., Harmsen, R., Rutten, C., Dittmann, F., Riviére, P., & Stabbat, P. (2017). *Baseline scenario of the heating and cooling demand in buildings and industry in the 14 MSs until 2050*. Heat Roadmap Europe. https://heatroadmap.eu/wp-content/uploads/2018/11/HRE4_D3.3andD3.4.pd

Fleiter, T., Fehrenbach, D., Worrell, E., & Eichhammer, W. (2012). Energy efficiency in the German pulp and paper industry – A model-based assessment of saving potentials. *Energy, 40*(1), 84–99. https://doi.org/10.1016/j.energy.2012.02.025

Fleiter, T., Herbst, A., Rehfeldt, M., & Arens, M. (2019). *Industrial innovation: Pathways to deep decarbonisation of industry_Part 2: Scenario analysis and pathways to deep decarbonisation*. Fraunhofer Institute. https://climate.ec.europa.eu/system/files/2020-07/industrial_innovation_part_2_en.pdf

Fleiter, T., Rehfeldt, M., Herbst, A., Elsland, R., Klingler, A.-L., Manz, P., & Eidelloth, S. (2018). A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. *Energy Strategy Reviews, 22*, 237–254. https://doi.org/10.1016/j.esr.2018.09.005

GNR. (2019). *WBCSD cement sustainability initiative - Getting the number the right project - Emissions report 2018*. https://gccassociation.org/gnr/. Accessed May 2021

Green, J. A. S. (2007). *Aluminum recycling and processing for energy conservation and sustainability*. ASM International. Accessed May 2021

Griffin, P. W., Hammond, G. P., & Norman, J. B. (2018). Industrial energy use and carbon emissions reduction in the chemicals sector: A UK perspective. *Applied Energy, 227*, 587–602. https://doi.org/10.1016/j.apenergy.2017.08.010

Harmsen, R., van Zuijlen, B., Manz, P., Fleiter, T., Elsland, R., Reiter, R., Palacios, A., Catenazzi, G., & Jacob, M. (2018). *Cost-curves for heating and cooling demand reduction in the built environment*. Heat Roadmap Europe. https://heatroadmap.eu/wp-content/uploads/2018/11/HRE4-D4.2-D4.3.pdf

IAI. (2020). *IAI Statistics*. https://international-aluminium.org/statistics/primary-aluminium-production/. *Accessed Mar 2021*

Institute for Industrial Productivity (IIP). (2014). *Industrial efficiency technology database - Glass*. http://www.iipinetwork.org/wp-content/Ietd/content/glass.html. Accessed May 2021

International Energy Agency. (2007). *Tracking industrial energy efficiency and CO2 emissions*. https://doi.org/10.1787/9789264030404-en

International Energy Agency. (2014). *Energy efficiency indicators, essentials for policy making*. https://www.iea.org/reports/energy-efficiency-indicators-essentials-for-policy-making. Accessed Sept 2021

International Energy Agency. (2016a). *Energy balances 2016 edition*.

International Energy Agency. (2016b). *World energy balances* (2016 edition). International Energy Agency. https://doi.org/10.1787/5138d8dd-en

International Energy Agency. (2017). *Energy efficiency highlights 2017*. International Energy Agency. https://www.iea.org/reports/energy-efficiency-2017

International Energy Agency. (2019). *Material efficiency in clean energy transitions*. https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions. Accessed Sept 2021

International Energy Agency. (2020). *CO2 emissions from fuel combustion*. International Energy Agency. https://doi.org/10.1787/co2-data-en

International Energy Agency. (2021). *World Energy Outlook 2021*. https://www.iea.org/reports/world-energy-outlook-2020. Accessed Apr 2021

Kermeli, K., & Crijns-Graus, W. (2020). Energy efficiency potentials on tope of the frozen efficiency scenario.https://doi.org/10.5281/zenodo.4436591

Kermeli, K., Edelenbosch, O. Y., Crijns-Graus, W., van Ruijven, B. J., Mima, S., van Vuuren, D. P., & Worrell, E. (2019). The scope for better industry representation in long-term energy models: Modeling the cement industry. *Applied Energy, 240*, 964–985. https://doi.org/10.1016/j.apenergy.2019.01.252

Kermeli, K., ter Weer, P.-H., Crijns-Graus, W., & Worrell, E. (2015). Energy efficiency improvement and GHG abatement in the global production of primary aluminium. *Energy Efficiency, 8*(4), 629–666. https://doi.org/10.1007/s12053-014-9301-7

Mantzos, L., Wiesenthal, T., Neuwahl, F., & Rózsai, M. (2020). *The POTEnCIA central scenario: An EU energy outlook to 2050* (JRC118353). Publications Office of the European Union. https://data.europa.eu/doi/10.2760/32835

Moya, J. A., Boulamati, A., Slingerland, S., van der Veen, R., Gancheva, M., Rademaekers, K. M., Kuenen, J. J. P., & Visschedink, A. J. H. (2015). *Energy efficiency and GHG emissions: Prospective scenarios for the aluminium industry*. Publications office of the European Union. https://data.europa.eu/doi/10.2790/263787

MPA, Ltd, C., & VDZ. (2019). *Options for switching UK cement production sites to near zero CO2 emission fuel: Technical and financial feasibility*. VDZ. https://www.vdzonline.de/wissensportal/publikationen/options-for-switching-uk-cement-production-sites-to-near-zeroco2-emission-fuel-technical-and-financial-feasibility

Owttrim, C. G., Davis, M., Shafique, H. U., & Kumar, A. (2022). Energy efficiency as a critical resource to achieve carbon neutrality in the pulp and paper sector. *Journal of Cleaner Production, 360*, 132084. https://doi.org/10.1016/j.jclepro.2022.132084

Remus, R., Aguado, M. M., Roudier, S., & Delagdo, S. L. (2012). *Best Available Techniques (BAT) reference document for iron and steel production*. Publications office of the European Union. https://data.europa.eu/doi/10.2791/97469

Rosen, R. A., & Guenther, E. (2015). The economics of mitigating climate change: What can we know? *Technological Forecasting and Social Change, 91*, 93–106. https://doi.org/10.1016/j.techfore.2014.01.013

Rutten, C., Fleiter, T., & Rehfeldt, M. (2017). *Background report 1: Review of heat saving technologies. Evaluation of techno-economic data for heat saving options from FORECAST*. Heat Roadmap Europe. https://dspace.library.uu.nl/bitstream/handle/1874/415396/HRE_BackgroundReport_ReviewIndustryHeatSavingOptions.pdf?sequence=1

Scalet, B. M., Garcia Munoz, M., Sissa, A. Q., Roudier, S., & Delgado Sancho, L. (2013). *Best Available Techniques (BAT) reference document for the manufacture of glass*. Publications office of the European Union. https://data.europa.eu/doi/10.2791/70161

Shao, Y. (2017). Analysis of energy savings potential of China's nonferrous metals industry. *Resources, Conservation and Recycling, 117*, 25–33. https://doi.org/10.1016/j.resconrec.2015.09.015

Statista. (2020). *Europe: secondary aluminium production 2020*. https://www.statista.com/statistics/1028859/europe-secondary-aluminum-production/. Accessed Mar 2021

USGS. (2020). *2017 minerals yearbook - Aluminum [advance release]*. United States Geological Survey. https://d9-wret.s3-us-west-2.amazonaws.com/assets/palladium/production/atoms/files/myb1-2017-alumi.pdf

Worldsteel. (2018). *Steel statistical yearbook 2018*. Worldsteel Association. https://worldsteel.org/wpcontent/uploads/Steel-Statistical-Yearbook-2018.pdf

Worrell, E., Blinde, P., Neelis, M., Blomen, E., & Masanet, E. (2010). *Energy efficiency improvement and cost saving opportunities for the U.S. iron and steel industry, An ENERGY STAR Guide for energy and plant managers*. Ernest Orlando Lawrence Berkeley National Laboratory. https://www.osti.gov/servlets/purl/1026806

Worrell, E., Faaij, A. P. C., Phylipsen, G. J. M., & Blok, K. (1995). An approach for analysing the potential for material efficiency improvement. *Resources, Conservation and Recycling, 13*(3), 215–232. https://doi.org/10.1016/0921-3449(94)00050-F

Worrell, E., Galitsky, C., Masanet, E., & Graus, W. (2008). *Energy Efficiency Improvement and Cost Saving Opportunities for the Glass Industry, an ENERGY STAR Guide for energy and plant managers*. Ernest Orlando Lawrence Berkeley National Laboratory. https://www.energystar.gov/sites/default/files/buildings/tools/Glass-Guide.pdf

Worrell, E., Kermeli, A., Energy, R., Change, T., Energy, & Resources. (2017). Meeting our material services within planetary boundaries. *5th International Slag Valorisation Symposium*, 461–470. http://slag-valorisation-symposium.eu/2017/wpcontent/uploads/downloads/Session%207/Ernst%20Worrell%20-%20Paper%20-%20Meeting%20our%20material%20services%20within%20planetary%20boundaries%20-%20SVS2017.pdf

Worrell, E., Kermeli, K., & Galitsky, C. (2013). *Energy efficiency improvement and cost saving opportunites for cement making - An ENERGY STAR Guide of energy and plant managers*. United States Environmental Protection Agency. https://www.energystar.gov/buildings/tools-andresources/energy-efficiency-improvement-and-cost-saving-opportunities-cement-making

Xavier, C., & Oliveira, C. (2021). *Decarbonisation options for the Dutch cement industry*. PBL Netherlands Environmental Assessment Agency and TNO Energie Transitie. https://www.pbl.nl/en/publications/decarbonisation-options-for-the-dutch-cement-industry

Zhang, S., Yi, B.-W., Worrell, E., Wagner, F., Crijns-Graus, W., Purohit, P., Wada, Y., & Varis, O. (2019). Integrated assessment of resource-energy-environment nexus in China's iron and steel industry. *Journal of Cleaner Production, 232*, 235–249. https://doi.org/10.1016/j.jclepro.2019.05.392

Zuberi, M. J. S., & Patel, M. K. (2017). Bottom-up analysis of energy efficiency improvement and CO2 emission reduction potentials in the Swiss cement industry. *Journal of Cleaner Production, 142*, 4294–4309. https://doi.org/10.1016/j.jclepro.2016.11.178