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A R T I C L E I N F O

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A B S T R A C T

Industry poses one of the biggest challenges in the renewable energy transition. In this paper, fossil fuels in the European industrial sector are replaced by renewable energy using a novel tool, IndustryPLAN, a planning tool for the assessment of national industrial sectors. In a bottom-up approach, each industry sub-sector is addressed with energy efficiency and fossil fuel replacement measures based on best available and innovative technologies, and in a top-down approach, the fuel and electricity consumption per country is analysed and decarbonised. The results indicate that: 1. Known technologies can decarbonise most of the industrial sector; 2. Costs and efficiencies are improved by energy savings and electrification; 3. Limiting bioenergy consumption is a critical challenge, emphasising the key role of energy savings and electrification, and the alternative of using hydrogen or hydrogen-based electrofuels will make the transition more expensive and induce energy losses. A full transition to renewable energy and a decarbonised industry sector may be possible before 2050, however, this requires that all investments are sustainable from 2030 onwards and that grid electricity is fully decarbonised. This paper presents several pathways toward 100% renewable energy supply in the European industrial sector and discusses the implications of the outlined scenarios.

1. Introduction

Worldwide, energy systems are undergoing a transition to renewable energy, and to support this, energy system scenarios have become an integrated part of the planning for this energy system transition. Most notably, in the European Union (EU), this is apparent in the vision put forward by the EU Commission – A Clean Planet for all scenarios [1], manifesting a commitment to the global objectives of the Paris agreement [2].

The industry sector must be an integral part of this ongoing renewable energy transition, and because of the extensive energy demand of the industrial sector, an efficient transition of the industry sector is essential to the overall energy system transition [3]. In the EU, industry constitutes about one-fourth of the total final energy demands, as it is illustrated in Fig. 1.

Despite the importance of the industry sector from an energy demand perspective, accurately depicting the industry sector and including it in energy system scenarios has traditionally been challenging, and decarbonisation has not been discussed in detail [5]. This is a result of multiple factors, including long facility lifetimes, low knowledge of mitigation options, and a lack of access to disaggregated energy demand data on a process, product, and fuel type level [6]. Access to such energy demand data in industries is generally subject to secrecy and confidentiality for competitive reasons, which inherently is counterproductive to comprehensive and accurate energy transition planning.

A further challenge to establishing industry energy scenarios is the general heterogeneity of the industry sector as it is comprised of a multitude of technologies, processes and products [7]. The result has typically been, that the industry sector is aggregated or otherwise simplified in energy system scenarios, thereby representing the industrial sector largely as a "black box" [8,9].

Country-level industry analyses, as conducted in the present study, are relevant and even necessary in outlining appropriate future pathways for the industry transition. These pathways and scenarios provide important insights on how to transition the industry sector, but equally important, they provide important inputs for holistic and integrated energy scenarios capturing all energy sectors and the cross-sectoral integration benefits [10]. However, while this is an important

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contribution to the energy system transition, such analyses do not replace in-depth and site-specific industry analyses, contributing with concrete learnings for individual industrial sites in implementing energy efficiency (EE) and fossil fuel replacement measures.

Previous research on the industry sector has emphasised studies with a narrow scope, e.g. with a focus on a specific country, sub-sector, product, or industrial site [11], resulting in a lack of comprehensive industry analyses across the entire EU.

In a study of the Danish industrial sector, Bühler et al. investigate the potential for electrification of industrial processes, finding that most of the Danish industrial energy demands can be electrified [12]. Fleiter et al. study the German industrial sector, establishing one potential transition pathway achieving an 83% reduction of greenhouse gas (GHG) emissions in 2050 [13]. In another study, Fleiter et al. also evaluated the energy savings potential of the German pulp and paper industry [14].

Focusing on the production of aluminium, Kermeli et al. derive energy and GHG abatement cost curves for 22 determined EE improvements, establishing technical and cost-effective energy and GHG savings potential [15]. Investigating the paper and pulp industry in Sweden and Finland, Lipiäinen et al. evaluate the effect of efficiency measures implemented from 2002 to 2017, arguing that the experiences from electrification in Sweden and Finland show great potential for GHG reductions in the paper and pulp industry worldwide.

The transition of the iron and steel sector is addressed in another study for Sweden, highlighting the potential for shifting to hydrogen-based processes [16], and in a study for the UK [17], presenting technology roadmaps for decarbonisation.

Meyers et al. conduct a study for the food and beverage industry in six European countries, finding significant emission reduction potential from EE improvement and implementation of renewables. It is found that several barriers exist to implementation, where the most important barrier determined was the investment costs [18].

Lechtenböhmer et al. present a top-down approach for analysing the decarbonisation of an aggregate European industry sector towards 2050, focusing mainly on electrification. The authors conclude that electrification of industry is technically possible, but needs to be combined with increased efficiency, biofuels, and carbon capture and storage [19].

Sorknæs et al. investigate the role of electrification within the industrial sector in a study comparing three renewable energy systems for Denmark [20]. The authors conclude that system benefits from electrification are connected to internal dispatchable power production capacity and that from an energy system perspective, direct electrification of heat demands should be prioritised over direct use of hydrogen.

The only existing model for bottom-up modelling of the industry sector is the FORECAST model developed by Fleiter et al. and used for developing scenarios for the long-term development of industry energy demands and GHG emissions, services, and household energy sectors [21]. The model is intended as a tool supporting strategic decision-making, with results categorized on a sub-sector level. The model has, to the best of our knowledge, not been applied for developing 100% renewable energy scenarios yet and is not publicly available.

IndustryPLAN, the model applied in this study, was first applied in [22], however, the tool was only sparsely applied to establish one 100% renewable energy scenario and some partially renewable scenarios. Hence, IndustryPLAN has not previously been applied for a comprehensive comparison of 100% renewable energy alternatives for industry.

In our review, we have identified a series of focused analyses on EE and the transition to renewable energy supply for specific sub-sectors of industry or individual countries. There is a severe lack of comprehensive analyses of the wider industrial sector and the EE and fossil fuel mitigation options available despite a few endeavours in the field. This is the primary gap this article seeks to fill.

1.1. Scope and structure

This paper investigates tangible pathways for transitioning the European industry to renewable energy by 2050, targeting the lacking middle ground of energy transition analyses of the industrial sector. The targeted scope presents a level of detail adequate for energy system planning, without delving into specificities of data and processes that

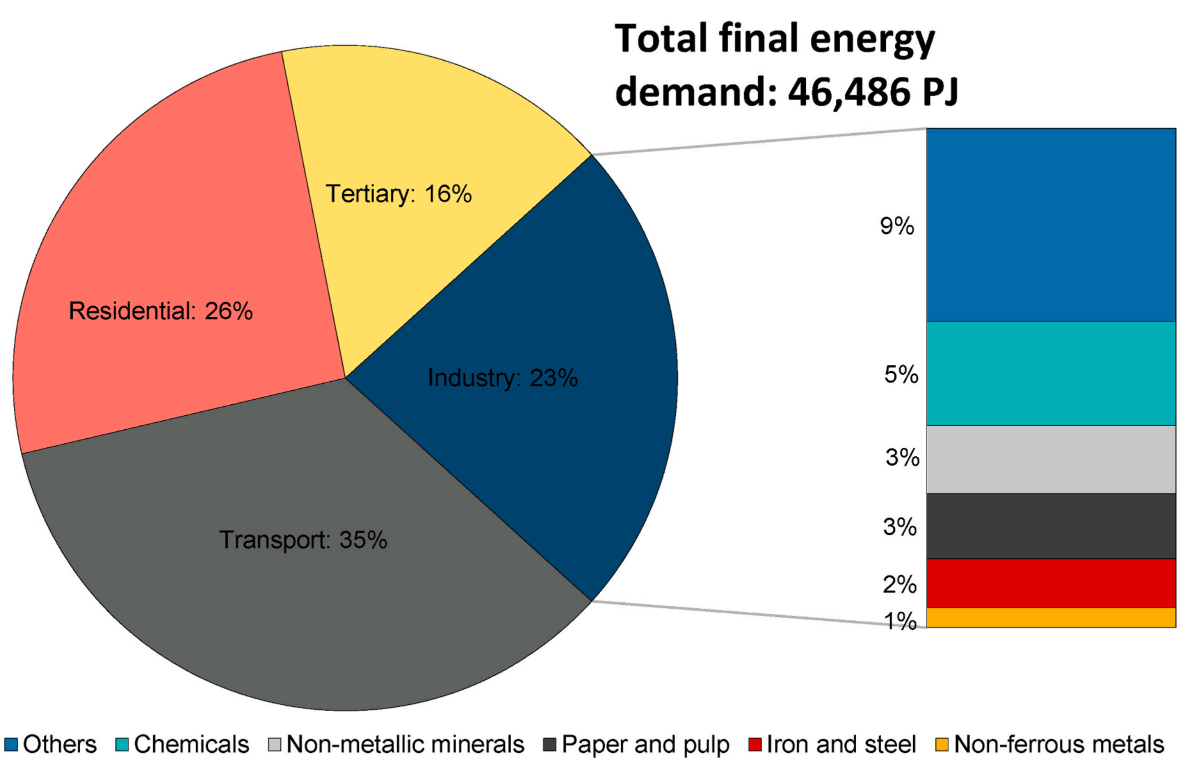

Fig. 1. *Total final energy demand per energy sector and industry sub-sector for EU27 + UK in 2019* [4].

would impede establishing holistic national industry scenarios.

The main novelty of the present study stems from the extent of the work in terms of geographic and industrial coverage, covering renewable energy transition scenarios for all EU27 + UK countries, and equally important, for all industrial sub-sectors. The modelled scenarios represent pathways for 100% renewable energy in all industrial sub-sectors, thus building upon previous industry transition studies presenting country, sub-sector, or site-specific renewable energy transition scenarios.

The paper is structured as follows. In Section 2 the methodology is presented, first by introducing the EE first-guiding principles, serving as the foundation of the modelling approach. This is followed by a model description, presenting the IndustryPLAN model along with key model inputs and an overview of the base year and frozen efficiency scenarios. Section 3 presents EE and fossil fuel replacement measures included in the 100% renewable energy scenarios, alongside cost curves for energy savings andGHG abatement, and an overview of the scenarios investigated. Section 4 presents a deep dive into the results of the modelled renewable energy scenarios, followed by a discussion of the implications and main uncertainties of the study in Section 5.

2. Methodology and model description

This section introduces the EE first principles on which the modelling of renewable energy industry scenarios is based, followed by a description of the IndustryPLAN model used for the actual industry scenario modelling. Finally, base year and frozen efficiency scenarios are presented with an emphasis on how these were established and applied in this study.

2.1. Energy efficiency first principle

Renewable energy industry scenarios are modelled based on guiding principles for EE [23,24]. The energy efficiency first principle is established based on a holistic energy system perspective, thereby considering not only sector-specific optimisation but also the technical and economic feasibility of the entire energy system.

Concretely, in the present study, the energy efficiency first principle is implemented in the form of a prioritised list of initiatives. This ensures that the industrial energy transition is conducted in a manner that first prioritises energy savings and other efficiency improvements, then sector integration and smart energy system coordination including electrification [25], and lastly, traditional fuel shifting from fossil fuels to biogas, solid biomass, hydrogen, and power-to-X fuels. Below, the guiding principles are seen in the form of a prioritised list, as they are applied in this study.

1. Material efficiency (recycling)
2. Best available technology (BAT) measures for EE improvements
3. Innovative measures for EE improvements
4. Electrification measures
5. Hydrogen fuel shifting measures
6. Solid biomass fuel shift

The applied guiding principles put great emphasis on limiting biomass consumption in the industrial sector as it constitutes a scarce resource that should generally be prioritised in hard-to-abate sectors, and where the greatest benefits can be obtained [26,27].

The renewable energy industry scenarios presented in this study represent a practical application of the guiding principles to demonstrate the importance of prioritising EE improvements alongside other fossil fuel replacement measures. This serves to limit biomass consumption in industry and to reduce investment costs on the supply side due to reduced energy demands as a result of increased EE.

2.2. IndustryPLAN introduction

The renewable energy scenarios are modelled with the use of the IndustryPLAN tool [22]. The tool, including all the data applied for this study, is open-access and is available online [28].

IndustryPLAN is a tool for bottom-up modelling of industry energy scenarios for all EU27 + UK countries, providing disaggregated results on product, sub-sector, and fuel types for individual countries. The tool is developed in Microsoft Excel based on a combination of VBA coding and Excel functions.

In IndustryPLAN, users can design scenarios with varying implementation of EE improvements and fossil fuel replacement measures. I.e., a user may choose to implement all the EE improvements, none of the improvements, or anything in between. Measures to be implemented are selected based on a least-cost principle, prioritising measures based on their cost per energy saved.

Cost curves can be established for both the cost per energy saved and for the cost of CO_2 abatement, as will be illustrated for the BAT measures specifically in the ensuing analysis. The resulting outputs are calculated as annual balances, e.g., final energy demands and CO_2 emissions per year, and hence it is not possible to assess hourly fluctuations of demands and products directly within the tool – nor the temporal integration with the rest of the energy system.

The tool relies on a range of inputs, most of which are included within the tool, such as a catalogue of EE and fossil fuel replacement measures, fuel prices, and emission factors. The user is provided with an interface for changing the included default values and for developing future industry scenarios. In Fig. 2 an overview of IndustryPLAN can be seen in terms of the main input data and outputs.

The seven industry sub-sectors included are further disaggregated into 23 individual products for which energy demands, EE, and fossil fuel replacement measures are included. An overview of the products included per sub-sector can be seen in Table 1, showing 2015 production volumes and future projections of industrial activity for 2030 and 2050 from Kermeli et al. [29]. The production volumes shown in Table 1 assume no changes to production technologies and thus represent a frozen efficiency scenario.

IndustryPLAN and the results of this paper are limited specifically to the industry sector and do not assess effects on a broader energy system level. The tool outputs (mainly aggregated yearly energy demands per industry sub-sector) are however suitable for further application in holistic energy system modelling of complete energy systems, as could be done in tools such as EnergyPLAN [30].

Further information is available in the following background reports on the frozen efficiency scenario [31], IndustryPLAN [22], and EE potentials [32].

2.3. Frozen efficiency and base year scenarios

While the main purpose of the study is to explore future renewable energy scenarios, for comparison a base year 2015 scenario and a frozen efficiency scenario for 2030 and 2050 are included.

The frozen efficiency scenario captures expected industrial developments, changes to product demand and other structural changes, but assumes no EE developments. The starting point for the frozen efficiency scenario is the industrial activity outlined in the European Commission's 2016 Reference Scenario [33] which includes final energy demand projections towards 2050, including assumed market trends and current policies. However, the scenario does not include details on the EE measures included.

The 2015 base year scenario is based on the PRIMES scenario for 2015 [34], which only includes aggregate final energy demands for the combined industry sector. This demand was disaggregated by sub-sector and main industrial products and average energy intensities per product (GJ/t), where such data was available. Future demands for the frozen efficiency scenario were determined assuming the product

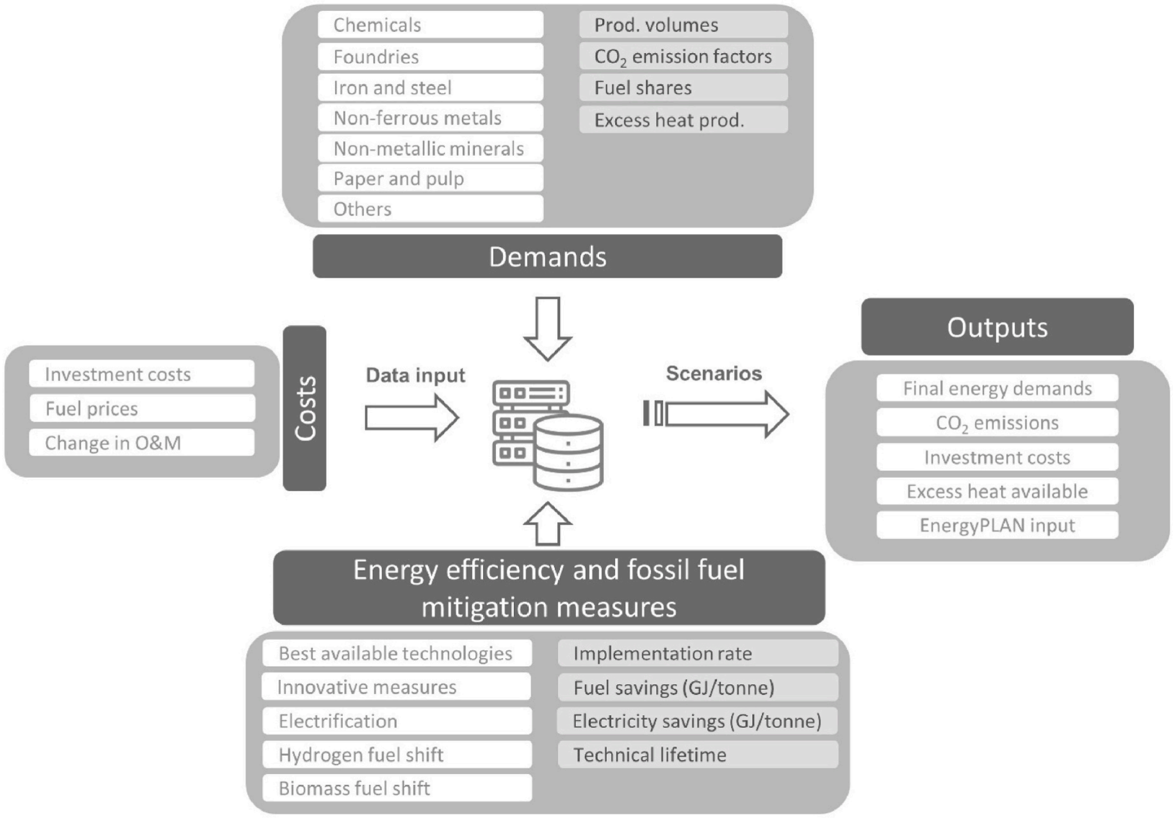

Fig. 2. IndustryPLAN model overview.

developments from PRIMES [34], but keeping the energy intensity at the 2015 level. Lastly, the energy demands were divided into fuel types (coal products, oil products, natural gas, biofuels and waste, heat, electricity, and hydrogen) by using the IEA database [35].

More details on the included 2015 base year and the frozen efficiency scenario are available in Kermeli and Crijns-Graus [32].

3. Measures enabling the renewable energy transition

This section introduces the EE and fossil fuel replacement measures functioning as the basis for the modelled industry renewable energy scenarios. Secondly, this section presents the modelled scenarios in terms of their implementation of measures, where an increasing extent of EE improvements and fossil fuel replacement measures are implemented.

3.1. *Energy efficiency and fossil fuel replacement measures*

Renewable energy scenarios are modelled based on a catalogue of EE and fossil fuel replacement measures, separated into the six categories presented in Section 2.1.

1. Material efficiency (recycling)
2. Best available technology (BAT) measures for EE improvements
3. Innovative measures for EE improvements
4. Electrification measures
5. Hydrogen fuel shifting measures
6. Solid biomass fuel shift

This catalogue of EE and fossil fuel replacement measures includes assumptions on product and process-specific implementation rates, investment costs, and lifetimes, as can be seen in Appendix A.

For all included EE and fossil fuel replacement measures, base year implementation rates, energy savings potentials (in GJ/tonne), investment costs (in 2015 EUR/tonne) and change in operation and maintenance costs (in 2015 EUR/tonne) were collected. Future implementation rates were assigned per technology for 2030 and 2050 based on the available literature, where for most technologies the implementation reaches 100% by 2050. The included EE and fossil fuel replacement measures are further documented in Ref. [29], however, assumptions and implementation rates should naturally be considered as estimations due to the uncertainty related to future technological developments.

Table 2 shows the total final energy demand of the Frozen efficiency scenario and Table 3 shows the total energy savings potential from the BAT measures combined with recycling, innovative measures, and electrification combined with H_2 fuel shift. Generally, the largest energy savings and CO_2 abatement potential are found in the iron and steel sub-sector with energy-intensive processes, followed by the non-metallic minerals and non-ferrous metals sub-sectors. The paper and pulp sub-sector has a significant potential for energy savings, but because the sub-sector is already largely based on electricity and biomass, the CO_2 abatement potential is low. The energy and CO_2 savings potential presented in Table 3 illustrate the energy and CO_2 savings potential for each of the implemented measures in isolation, i.e., electrification and H_2 fuel shifting without concurrent implementation of BAT measures and innovative measures. As can be seen in Table 3, extensive electrification and H_2 fuel shifting without emphasis on EE improvements cause an increase in energy demand in the iron and steel and others sub-sectors. The combined savings potential in Table 3 leaves 2.73 MT CO_2 (0.65%) for which it is assumed that solid biomass would replace the last remaining fossil fuel.

Cost curves are derived for the BAT measures based on the annualised investment costs, total energy and CO_2 savings, fuel cost savings, and additional O&M costs incurred by implementing the EE and fossil fuel replacement measures. Below in Table 4 the assumed fuel prices for 2030 and 2050 respectively can be seen. It should be noted, that because

Table 1
Overview of sub-sectors and production volume developments included in IndustryPLAN model as the foundation for the Frozen Efficiency scenario [29].

Industrial sub-sector	Product	2015 [kt]	2030 [kt]	2050 [kt]
Chemicals	Carbon black	998	1,121	1,166
Chemicals	Ethylene	16,810	18,091	18,306
Chemicals	Methanol	1,438	1,725	1,812
Chemicals	Ammonia	17,394	18,146	18,137
Chemicals	Soda ash	6,025	6,323	6,252
Foundries	Ferrous metals casting	10,185	10,912	11,091
Foundries	Non-ferrous metals casting	3,672	3,972	3,972
Iron and steel	BF/BOF[a] steel	100,864	106,921	110,129
Iron and steel	Pig iron	93,596	104,860	106,780
Iron and steel	Rolled steel	150,924	143,279	119,453
Iron and steel	EAF[b] steel	65,429	69,355	71,436
Iron and steel	Coke oven coke	32,586	34,432	34,724
Non-ferrous metals	Aluminium primary	2,242	2,422	2,398
Non-ferrous metals	Aluminium secondary	3,300	3,488	3,438
Non-metallic minerals	Cement	168,170	200,917	204,500
Non-metallic minerals	Flat glass	11,617	12,846	13,387
Non-metallic minerals	Container glass	15,317	15,844	14,149
Paper and pulp	Tissue paper	7,175	7,762	7,889
Paper and pulp	Graphic paper	34,566	37,041	37,609
Paper and pulp	Board and packag. Paper	46,114	49,512	50,606
Paper and pulp	Chemical pulp	25,582	27,000	27,693
Paper and pulp	Mechanical pulp	8,236	8,712	8,939
Paper and pulp	Recovered fibre pulp	21,294	22,489	23,247

[a] Blast furnace/Basic oxygen furnace.
[b] Electric arc furnace.

Table 2
Frozen efficiency final energy demands and CO_2 emissions for EU27 + UK.

Frozen efficiency scenario	Energy demand 2030	Energy demand 2050	CO_2emissions 2030	CO_2emissions 2050
Sub-sector	[PJ]	[PJ]	[Mt CO_2]	[Mt CO_2]
Chemicals	2,287.64	2,314.04	73.78	62.13
Foundries	96.15	97.50	7.05	6.43
Iron and steel	2,241.50	2,223.12	142.23	126.10
Non-ferrous metals	423.89	427.69	8.69	7.52
Non-metallic minerals	1,815.14	1,843.02	78.38	67.09
Paper and pulp	1,568.86	1,611.44	22.51	17.68
Others	5,095.68	6,033.05	130.45	130.32
Total	**13,528.86**	**14,549.86**	**463.09**	**417.27**

the intention of the study is to perform a socioeconomic assessment, taxes are not included in the fuel prices. Projecting fuel prices is a difficult task and not a primary goal of this study, but it is necessary to include some estimations of prices to properly evaluate the value of energy and fuel savings. Fuel prices are considered static and are not impacted by changes within the industry sector. In addition to the fuel prices, the cost curves are subject to the discount rate included in the economic calculations. For this study, to evaluate the effect of a low and high discount rate, results for rates of 3% and 15% are included, respectively. The 3% discount rate is selected to align with the socio-economic perspective, while the 15% discount rate is selected to take into account investment hurdles faced by EE in industries.

The cost curves consist of steps of varying length and height; this is due to variance in the energy savings potential and the difference in cost from one measure to the next. For the BAT measures in Fig. 3, both in 2030 and 2050, it can be seen that approximately 50% of all energy savings, regardless of industry sub-sector, can be implemented at a negative cost from a socio-economic perspective. These measures thus represent "no-regrets" opportunities, that should be pursued as part of the industrial energy transition, whereas the implementation of the more expensive measures towards the top end of the spectrum depends on the extent to which other options are available and the depth of the required transition.

The CO_2 abatement curves in Fig. 4 show a similar picture to the results seen in Fig. 3. About 80% of the CO_2 emission reduction potential in the non-ferrous metals, iron and steel, and non-metallic minerals sub-sectors, and the entire potential of the chemicals and paper and pulp sub-sectors can be realised as net positive investments from a socio-economic perspective.

In Figs. 5 and 6 cost curves for conserved energy and CO_2 abatement can be seen with a 15% discount rate as opposed to the 3% discount rate employed in Figs. 3 and 4. While it is apparent that the discount rate does significantly impact the cost curves, it can also be seen that significant potentials for energy savings and CO_2 abatement remain available at low and negative cost levels from a socioeconomic perspective. Hence, even with the traditionally higher discount rates applied by industries for business economic cost-benefit assessments, EE and fossil fuel replacement measures should be pursued in the immediate future, from both an environmental and economic perspective. However, it should be noted, that the lifetimes of the measures are assumed to correspond to the technical lifetimes, whereas in a true business economic assessment, industries likely require a shorter payback time.

The same principle for establishing cost curves can be applied to the innovative EE measures, electrification measures, and hydrogen fuel shifting measures, but because fewer measures are identified per category, the results are less interpretable. Instead, an overview of these additional measures is included in Appendix A.

3.2. Scenario overview

In addition to the frozen efficiency and base year scenarios presented in Section 2.3, four 100% renewable industry scenarios are established; an overview of these scenarios is presented in Table 5. It should be emphasised that in all scenarios (1–4) 100% renewable energy is achieved. However, different measures are applied for mitigating the fossil fuel energy demand.

The scenarios outline that there is not only one path to the decarbonisation of the industry sector but rather that an array of pathways exists, and these should be explored in the holistic industry sector scenarios. Furthermore, the scenarios aim to illustrate, that while conversion to bioenergy is a flexible and technically feasible option for many processes, consumption needs to be reduced where possible, due to the scarcity of the resource. Limiting bioenergy consumption is central to the EE first principles which have guided the scenarios, as was described in Section 2.1.

In Scenario 1 "Low EE", the recycling rate is kept low and BAT technologies are only partially implemented, while innovative measures are not at all implemented. Electrification is only implemented for 50% of the available potential, and no hydrogen fuel shift is implemented. Scenario 1 is hence denoted as the Low EE scenario and will rely on solid biomass for a significant portion of the energy demand.

In Scenario 2 "High EE", a high recycling rate is implemented in addition to implementing the full potential for BAT technologies and innovative measures. However, the electrification rate and implementation of hydrogen fuel shifting measures remain at the same level as in Scenario 1.

In Scenario 3 "High EE and elec.", recycling, BAT technologies, and innovative measures remain at the same level as in Scenario 2, but the

Table 3
Total energy and CO_2 savings potential per sub-sector from BAT measures and recycling, innovative measures, and electrification and H_2 fuel shift for EU27 + UK.

	Sub-sector	Energy savings potential 2030 [PJ]	Energy savings potential 2050 [PJ]	CO_2savings potential 2030 [Mt CO_2]	CO_2savings potential 2050 [Mt CO_2]
BAT and high recycling	Chemicals	133.10	199.89	4.99	6.17
	Foundries	6.58	14.96	0.49	1.01
	Iron and steel	487.07	931.21	37.55	65.56
	Non-ferrous metals	63.30	143.76	1.69	3.42
	Non-metallic minerals	308.31	612.58	13.00	22.69
	Paper and pulp	38.24	73.98	0.11	0.15
	Others[a]	607.50	1,332.65	19.49	37.40
	Total	**1,644.10**	**3,309.04**	**77.32**	**136.41**
Innovative measures	Chemicals	0.05	0.05	0.00	0.00
	Foundries	0.00	0.00	0.00	0.00
	Iron and steel	76.76	237.21	5.71	16.32
	Non-ferrous metals	1.87	34.39	0.00	0.00
	Non-metallic minerals	34.21	279.10	1.81	12.50
	Paper and pulp	22.10	158.51	0.12	1.33
	Others[a]	0.00	0.00	0.00	0.00
	Total	**135.00**	**709.27**	**7.64**	**30.15**
Electrification and H_2	Chemicals	29.12	154.90	6.26	46.62
	Foundries	6.97	27.73	1.29	4.79
	Iron and steel	10.73	−460.25	0.73	23.68
	Non-ferrous metals	3.50	15.38	0.25	0.81
	Non-metallic minerals	31.54	186.56	4.34	35.81
	Paper and pulp	33.20	181.58	2.78	17.56
	Others[a]	−63.49	2,037.80	7.41	118.72
	Total	**51.58**	**2,143.70**	**23.06**	**247.99**
	Grand total	**1,830.67**	**6,162.01**	**108.02**	**414.54**

[a] Others-sector is an average of the savings potential from the other sectors as no specific measures are identified for this sector.

Table 4
Fuel prices included for establishing cost curves for EE measures.

	Fuel price [EUR/GJ] 2030	Fuel price [EUR/GJ] 2050	Source
Coal and coal products	2.73	2.69	IEA WEO 2020 (stated policies) [36]
Oil products	12.30	13.92	IEA WEO 2020 (stated policies) [36]
Natural gas	7.34	8.92	IEA WEO 2020 (stated policies) [36]
Biomass	16.08	16.48	Danish Energy Agency fuel price projections [37]
Heat	18.10	18.10	European District heating price series [38]
Electricity	12.70	12.70	Danish Energy Agency fuel price projections [37]
Hydrogen	24.80	24.80	IEA Future of hydrogen [39]

electrification rate is increased to 100% of the potential.

Finally, in Scenario 4 "High EE and elec./H_2", hydrogen fuel shifting measures are implemented alongside the EE and fossil fuel replacement measures included in Scenarios 2 and 3.

4. 100% renewable energy industry scenarios

This section presents the resulting four 100% renewable energy industry scenarios developed for this study and compares these to a 2015 Base year scenario and a Frozen Efficiency scenario. Results are presented in terms of final energy demand, disaggregated by industrial sub-sector, and energy sources, for both an aggregate of all EU27 + UK countries and per country. Scenarios were modelled for all EU27 + UK countries, however, for readability and clarity, country-specific results are only shown for the 14 countries with the highest final energy demand. The remaining 14 countries are, for visualisation purposes, aggregated as one, resulting in a country category of "Others". Data for all countries is however available in Appendix A.

4.1. Results for a combined EU27 + UK

Figs. 7 and 8 show the final energy demand for the established scenarios, disaggregated first by fuel type and then by industrial sub-sector. The others sub-sector (consisting, e.g., of food production) is an average of the remaining sectors, as no specific measures are identified for this sector.

The frozen efficiency scenario clearly illustrates that without EE improvements, energy demands in the industry sector can be expected to increase in both 2030 and 2050. The effects of this trend can however be partially negated by the EE improvements included in the Low EE scenario, and entirely by the improvements in the High EE scenario with a final energy demand below the 2015 base year in 2050. In all scenarios, it is apparent that electrification is highly prominent, even in the Low EE and High EE scenarios, where only 50% of the possible electrification measures are included.

Bioenergy is used extensively in the Low EE scenario due to the limited implementation of EE measures and only partial electrification, resulting in a bioenergy demand that is almost five times the demand in the 2015 base year scenario. In the Low EE scenario, bioenergy is used extensively for heating, even in relatively low-temperature processes where electrification and other measures are technically feasible.

Implementing conversion to hydrogen-based processes in the High EE and elec./H_2 scenario makes it possible to further reduce biomass demand. The potential for introducing hydrogen is limited to high-temperature processes found mainly in the chemicals and iron and steel sub-sectors. This potential is relatively limited until 2030 but increases towards 2050 because of expected increases in implementation rates. Implementing hydrogen-based processes would, from an energy system perspective, also introduce additional energy losses because of the losses incurred from hydrogen production e.g., from electrolysis. It should be noted, that for this study, the actual production side of

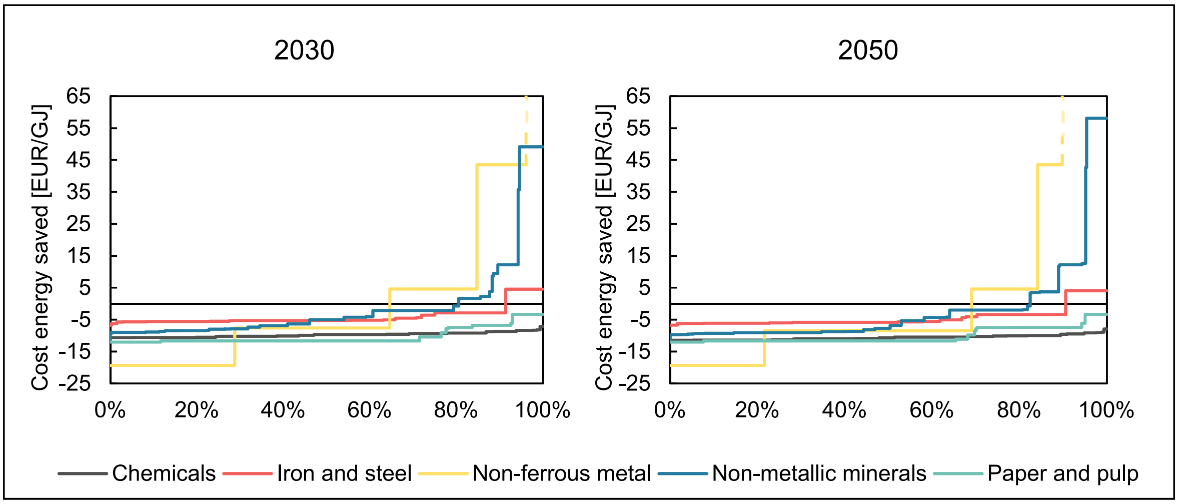

Fig. 3. Cost of conserved energy for BAT measures relative to the total savings potential from BAT measures [EUR/GJ-saved] for EU27 + UK (3% discount rate). Note that non-ferrous metals extend beyond the graph to 114.98 EUR/GJ in 2030 and 114.09 EUR/GJ in 2050.

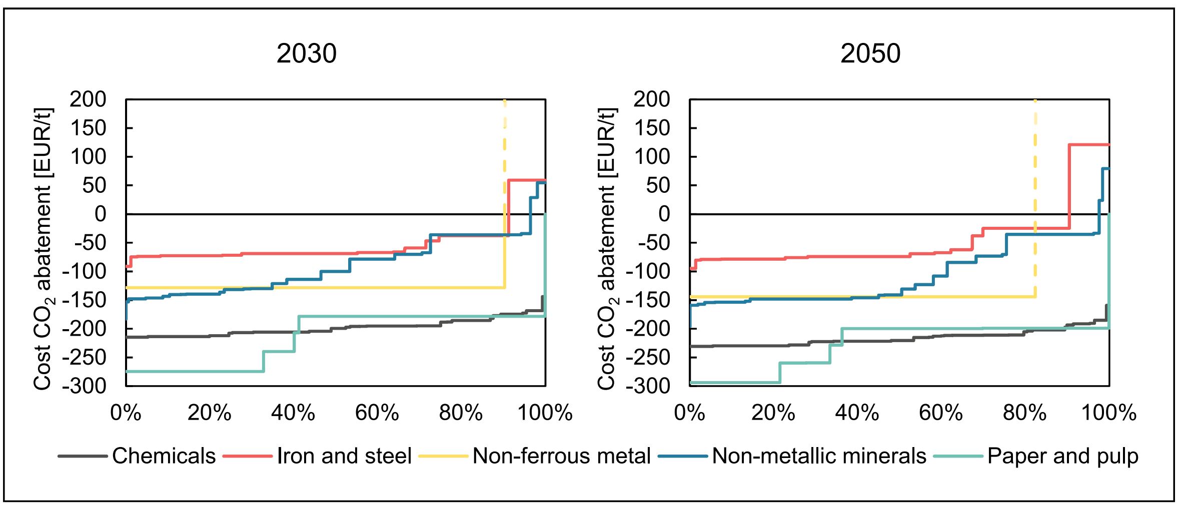

Fig. 4. Cost of CO_2 abatement for BAT measures relative to the total CO_2 savings potential from BAT measures [EUR/t] for EU27 + UK (3% discount rate). Note that non-ferrous metals extend beyond the graph to 1,934.60 EUR/t in 2030 and 1,760.69 EUR/t in 2050.

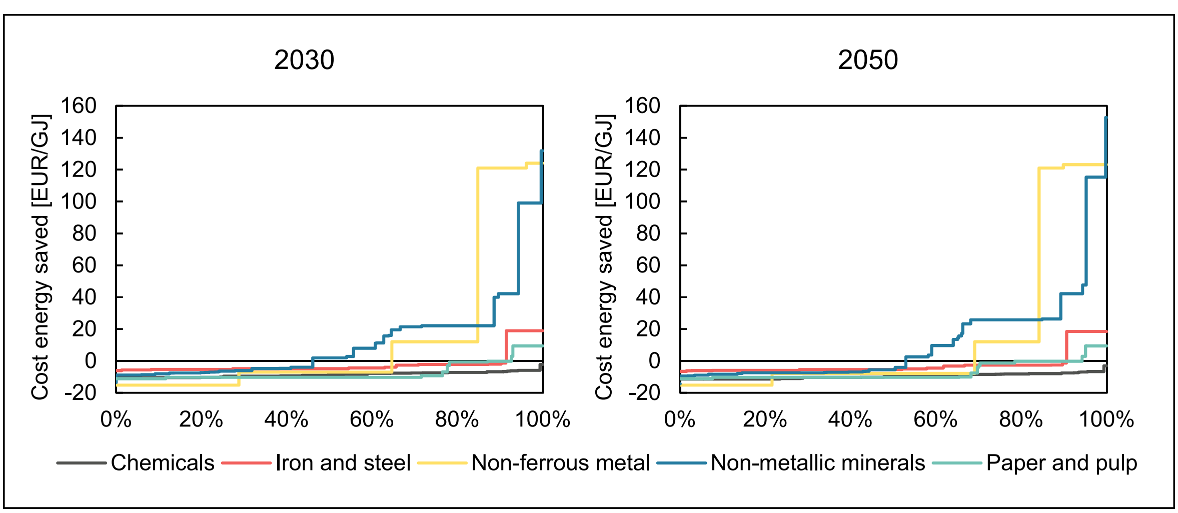

Fig. 5. Cost of conserved energy for BAT measures relative to the total savings potential from BAT measures [EUR/GJ] for EU27 + UK (15% discount rate).

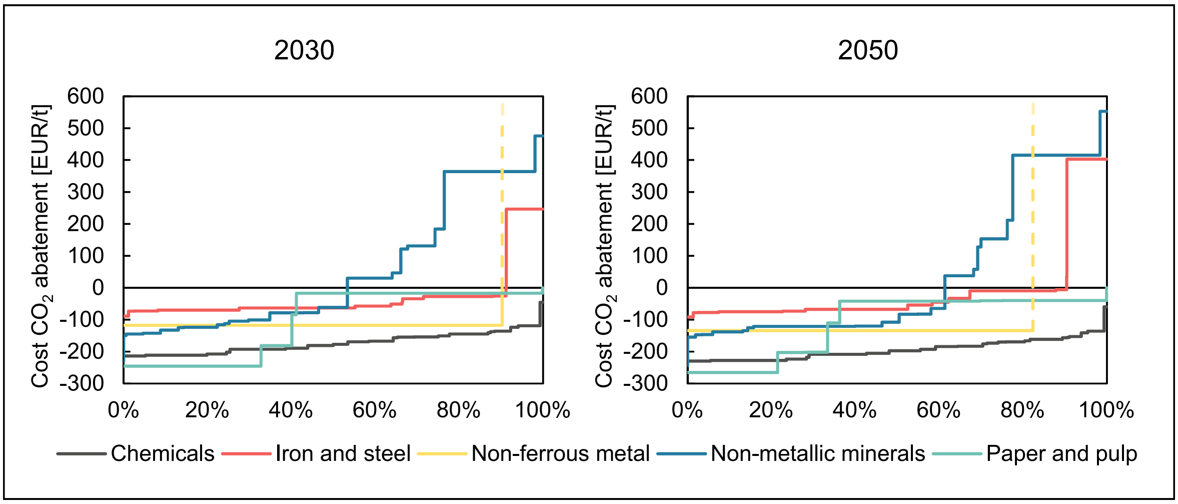

Fig. 6. Cost of CO_2 abatement for BAT measures relative to the total CO_2 savings potential from BAT measures [EUR/t] for EU27 + UK (15% discount rate). Note that non-ferrous metals extend beyond the graph to 2,086.89 EUR/t in 2030 and 1,901.30 EUR/t in 2050.

Table 5
Overview of modelled 100% renewable energy scenarios for industry.

	Scenarios	Iron & steel	Non-metallic minerals	Non-ferrous metals	Chemicals	Paper and pulp
	Frozen efficiency	No uptake of EE. EE remains at the 2015 level.				
	1) Low EE	Limited adoption of EE measures (BATs); No increase in material efficiency; Partial electrification (50% of potential – see electrification measures in 3); Solid biomass fuel shift for remaining fossil fuel demand.				
	2) High EE	Wide adoption of BATs; Innovative measures; Partial electrification (50% of potential – see electrification measures in 3); Solid biomass fuel shift for remaining fossil fuel demand; Material efficiency improvements:				
		Share of EAF steel increased from 39% to 67%	Clinker to cement ratio decreased from 76% to 60%	Share of secondary aluminium increased from 60% to 70%	–	Share of paper from recovered fibres increased slightly
Renewable energy scenarios	**3) High EE and elec.**	Wide adoption of BATs; Material efficiency same as in high EE; Innovative measures; Solid biomass fuel shift for remaining fossil fuel demand; 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
	4) High EE and elec./H_2	Wide adoption of BATs; Material efficiency same as in High EE; Innovative measures; Electrification measures; Solid biomass fuel shift for remaining fossil fuel demand; 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

hydrogen is not considered – hydrogen is strictly considered as a demand that needs to be satisfied within the entire energy system. Hence, the final and primary energy demand, from a system perspective, would be greater than what is depicted in the scenario due to the electricity required for hydrogen production.

In Fig. 9, the resulting biomass demand is disaggregated per industry sub-sector. Most obvious is perhaps the significant biomass demand needed in the Low EE scenario. This is a result of the 100% renewable energy target being upheld, even if the EE and fossil fuel replacement measures implemented are insufficient to support this transition. A biomass consumption of almost 5,000 PJ as seen in the Low EE scenario in 2050 corresponds roughly to the total European consumption of biomass in 2018 [40], and consuming that amount alone in industry is unlikely to be feasible.

In Fig. 10 the electricity consumption per industry sub-sector is shown, illustrating that the others sub-sector by far consumes the most electricity. This is a result of the relatively low-temperature processes, e.g., food and drink production, belonging to this sub-sector, making it highly suitable for electrification. Interestingly, the highest electricity consumption is seen in the Low EE scenario, even despite the full potential for electrostriction is not implemented. This is caused by the limited implementation of EE in the Low EE scenario resulting in higher

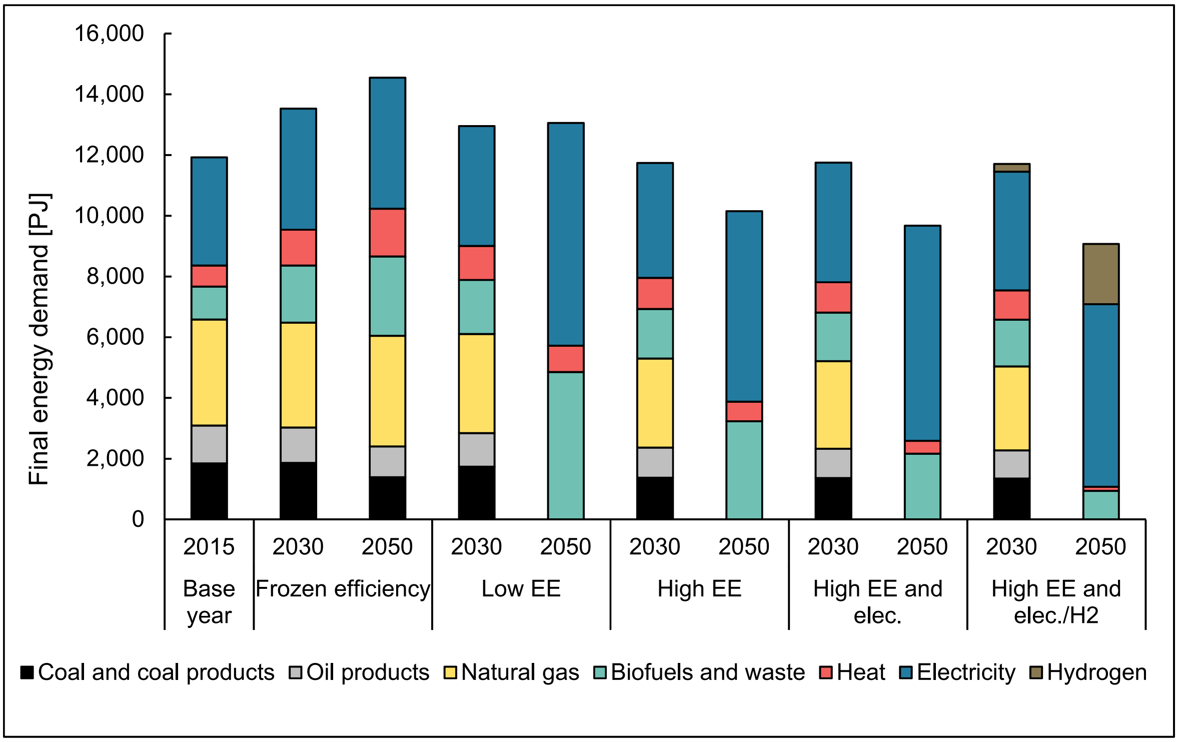

Fig. 7. Final energy demand in industry by scenario disaggregated by fuel type (EU27 + UK).

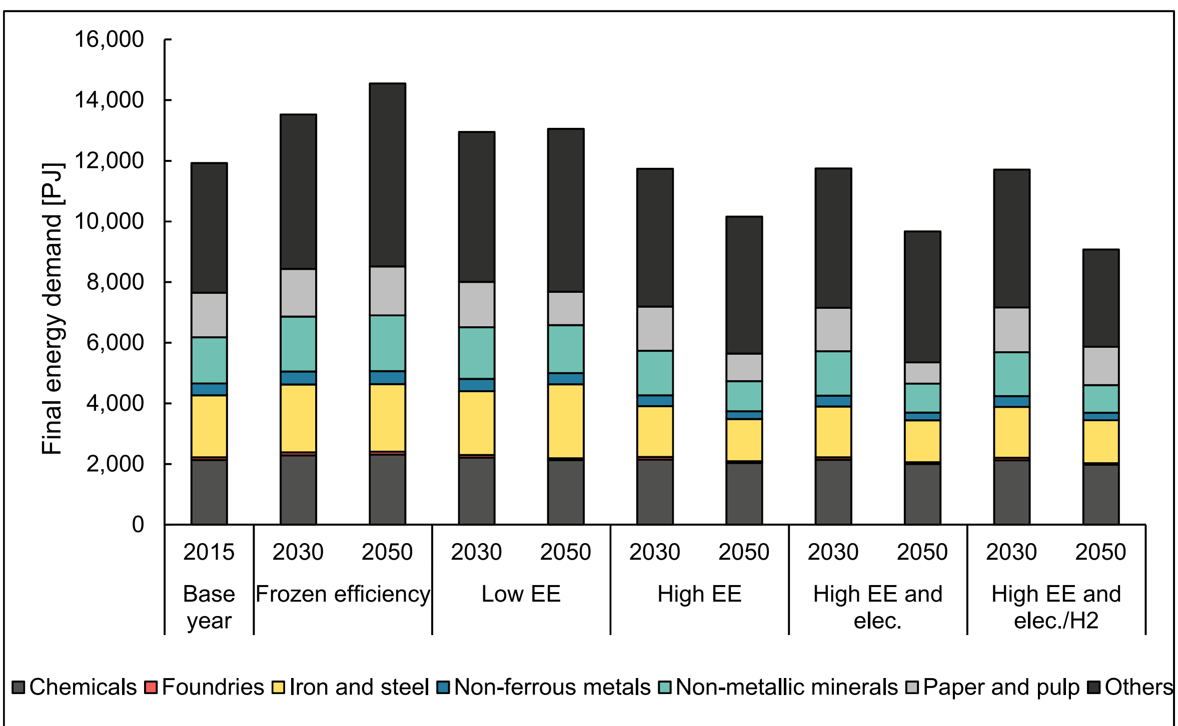

Fig. 8. Final energy demand by scenario disaggregated by industrial sub-sector (EU27 + UK).

total energy demands compared to the other scenarios and thereby also higher electricity consumption.

Looking at the investment costs incurred per scenario as shown in Fig. 11, most investments occur after 2030. This is a result of the assumed implementation rates, where most of the potential is to be realised after 2030 when technologies are maturing and can be implemented to a higher extent. Compared to the annual fuel and electricity cost, the annualised investment cost required for the EE and fossil fuel replacement measures constitutes only 6.49%–14.91% of the total annual cost in 2050.

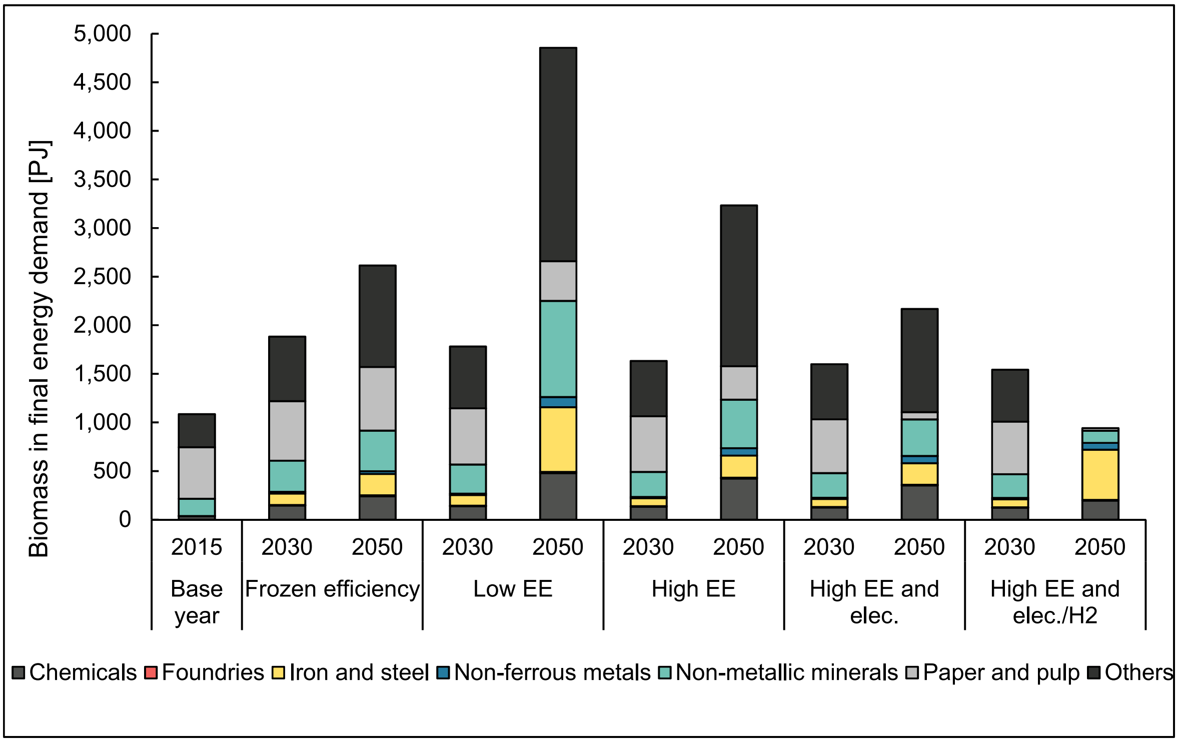

Fig. 9. Biomass consumption in final energy demand for industry (EU27 + UK).

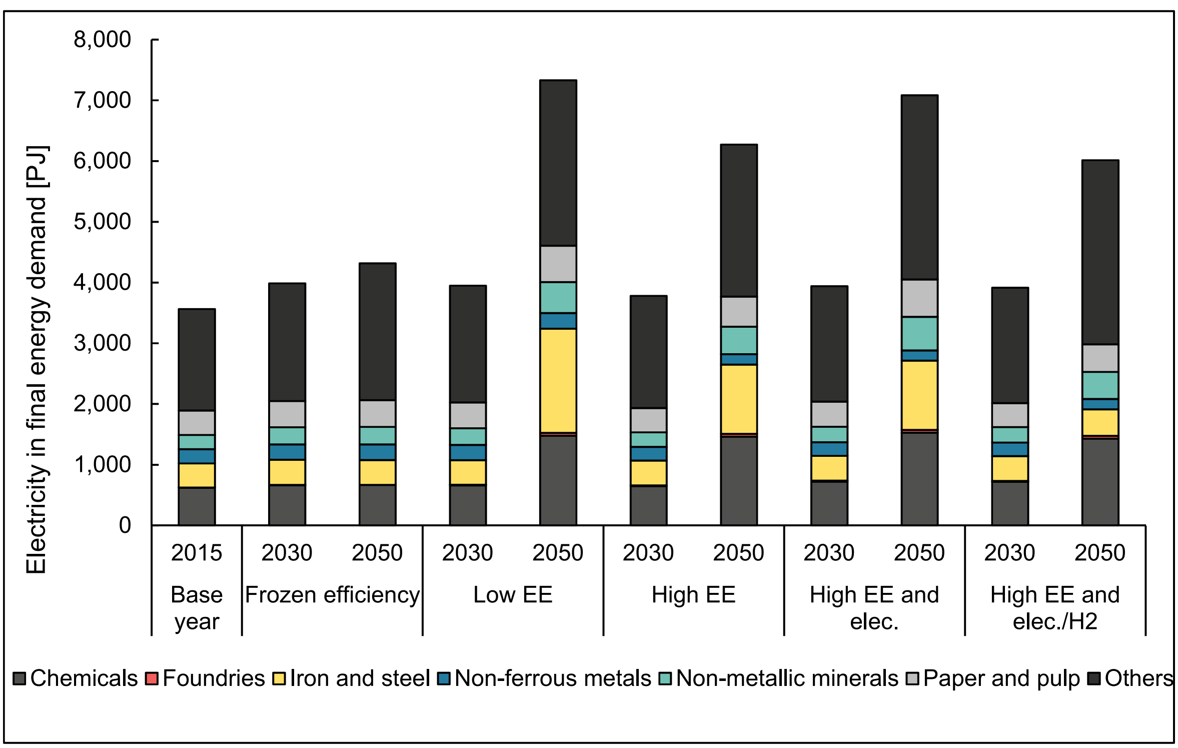

Fig. 10. Electricity consumption in final energy demand (EU27 + UK).

4.2. *Country specific results*

Country-specific results for final energy demand are presented in Figs. 12 and 13, showing that, on a country level, Germany dominates the other European countries in terms of final energy demand, far exceeding the demands of all other European countries. This remains the case also in the high EE scenarios, despite the vast potential for energy savings in the German industrial sector. An important takeaway from the country-specific results is that all countries and sub-sectors show significant potential for energy savings. Focus and attention to EE improvements and the general transition of the industry sector should therefore not be limited to specific countries with a certain industrial

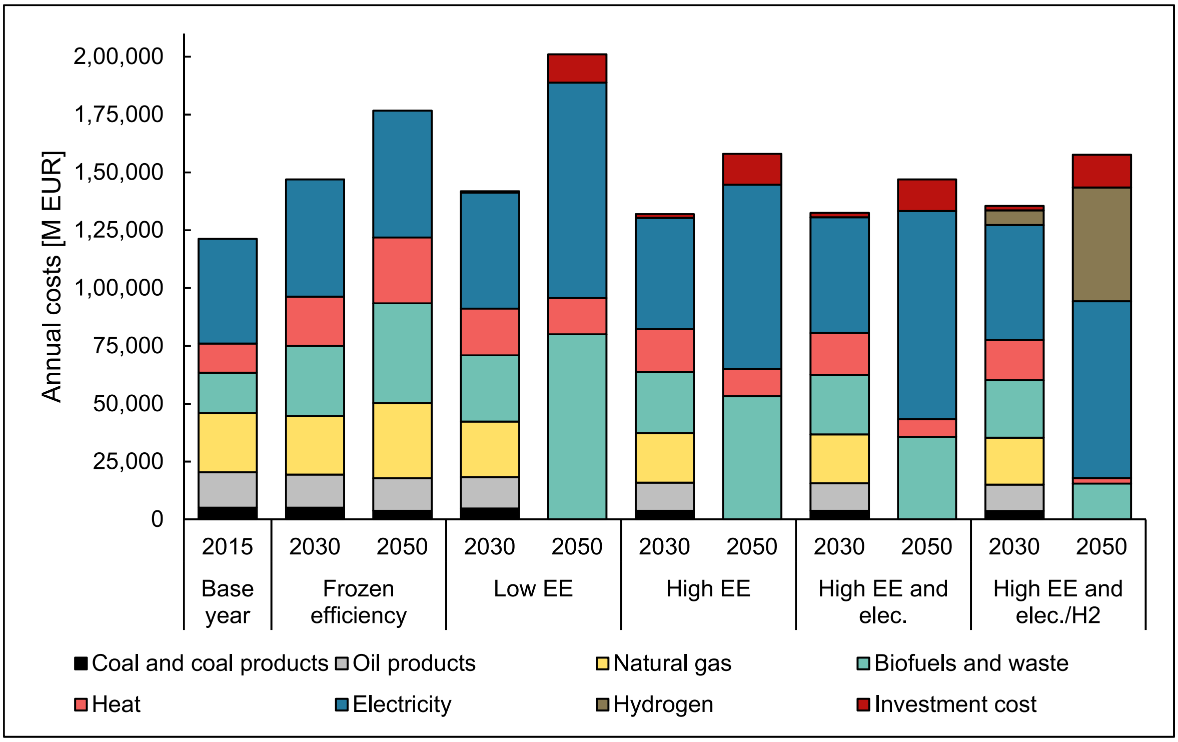

Fig. 11. Annual fuel and investment costs for industry by scenario (EU27 + UK).

typology but can actively be pursued by all EU27 + UK countries.

As seen in Fig. 13, for all countries, electrification is by far the most important enabler of the industrial energy transition, exceeding all other energy types in all scenarios. Largely a result of the sheer size of the industrial sector Germany is also expected to be the largest consumer of biomass. This can however be avoided almost entirely through a strong emphasis on EE improvements, electrification, and to a lesser extent, conversion to hydrogen-based processes.

5. Discussion

Technologies such as geothermal heating and concentrated solar heating (CSH) [41] have not been included in the developed scenarios due to a lack of concrete technical and economic data but may be relevant in the future for the renewable energy transition of the industry sector. Geothermal heating and CSH are relevant for temperatures up to approximately 200 °C, and possibly even 220 °C in the future, making them suitable for a significant portion of the industrial heat demand. While no actual scenarios are established with this technology, an estimation of the potential is included, based on a 200 °C supply temperature (Table 6). From this estimate, it can be assumed that low-temperature technologies such as geothermal heating or CSH could supply upwards of 30% of the total industrial energy demand in the future, mainly in sub-sectors with lower temperature demands, like in the paper and pulp sub-sector, or the food products included in the others sub-sector. A significant portion of this demand could also be supplied by heat pumps; hence the actually available potential would be lower.

The transition to renewable energy sources is often in energy systems accompanied by discussions of flexibility due to the fluctuating nature of most renewable energy sources [42]. Similarly, for the industry sector, arguments could be made, that in the future the industry sector to a higher extent needs to add flexibility to the overall energy system, potentially by having some part of the industry demands be flexible, or by adding storage capacity, e.g., heat storage, allowing for flexible operation. Flexibility could also be implemented by changing the fuel and electricity cost structures to incentivise flexible consumption, for example as seen in the district heating sector [43], where flexible electricity grid tariff rates have been suggested. Similar principles could be transferred to the industry sector, with electricity price structures based not only on a volumetric measure of energy but also on the peak load and connected capacity. This may be increasingly relevant as the industry sector is electrified (along with the rest of the energy system) and could be explored in greater detail in further research, as it has not been an ambition for this study to outline the flexibility potential of the industry sector.

The bottom-up nature of this study is also a limitation of the study in the sense that only existing solutions or expected (innovative) technologies are included. It is however unavoidable that new technologies arise in the future that are not included in this analysis. This could include CSH technologies, geothermal heating, or carbon capture utilisation and storage technologies. This is to some extent a limitation of the model, as such technologies may be technically feasible for implementation in the industry sector [44], but the absolute potential for implementation remains uncertain. Excluding carbon storage technologies is also a result of the applied EE first principles, prioritising savings and fuel shifting measures where possible instead of relying on carbon storage measures.

The developed scenarios do leave a small portion (4.4%) of the industrial energy demand without concretely identified technologies or measures for the shift to renewable energy sources. We assume that this energy demand can be converted to solid biomass-based technologies, which, due to the general flexibility of biomass heat supply technologies seems highly likely but is nevertheless an essential assumption to the study. This is a result of the bottom-up methodology applied, and while we can strive for it, it is not possible to have complete and irrefutable knowledge of all the future technologies needed for the industry transition.

The study includes country-specific production volumes based on the EU Reference scenario from 2016 [33] combined with product-specific implementation rates. However, future industrial activity is uncertain, and as a result, so are the included projections of production volumes.

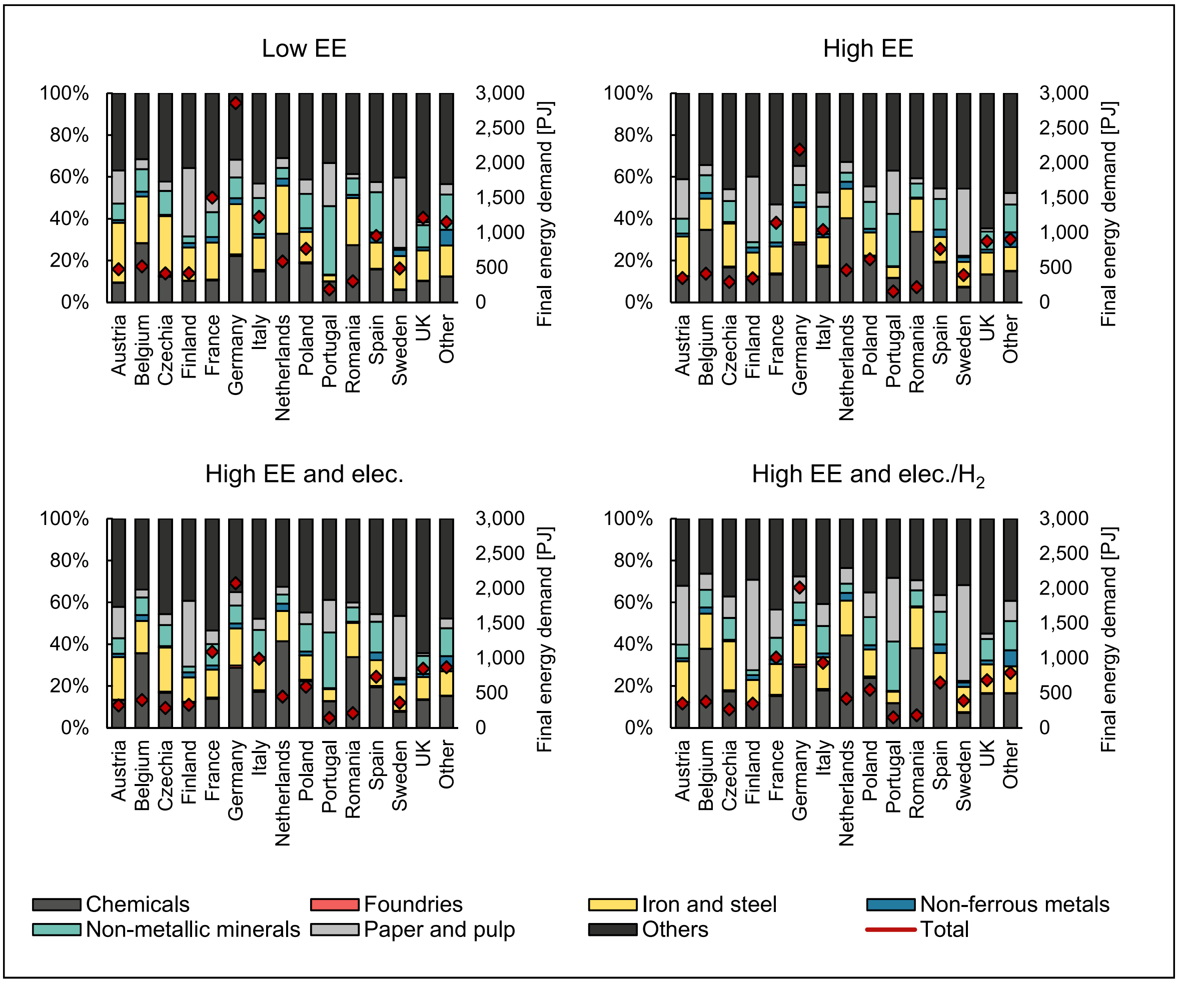

Fig. 12. 2050 country-specific final energy demand distribution per industrial sub-sector (left axis) and total final energy demand [PJ] (right axis) as indicated by the red marker. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Material demand within the EU could increase or decrease more than what is projected due to a multitude of factors such as changes in behaviour, population growth, or economic growth. Furthermore, the projected industrial activity does not consider any potential future relocation of industry outside or inside the EU. Industries may in the future choose to relocate from outside of the EU to inside to increase self-sufficiency, or on the contrary, decide to relocate outside of the EU to reduce labour costs or for better access to a global market. Such effects are not considered in this study where the same projection for industrial activity is applied across all scenarios. Implementation rates for EE measures are assumed to be the same across all countries based on the assumption that technologies are expected to develop equally across countries, however, this may not be the case, and some countries may establish themselves as frontrunners in the industry energy transition resulting in different implementation rates.

The potential for recovering excess heat from industry for use outside of industry, e.g., in district heating, was not evaluated in this study. Such an analysis was however conducted by Manz et al. for EU 27 + UK, but only for a business-as-usual scenario and only covering approximately 60% of the industrial energy consumption [45]. Assessing the excess heat potentials from industry in 100% renewable energy scenarios such as the scenarios established in the present study should be prioritised in future research.

The intention of this study is not to present an optimisation exercise – on the contrary, the aim is to illustrate the role and benefits of EE improvements in industry and the feasibility of 100% renewable energy, not strictly to argue for one optimal solution. It should furthermore be considered that sector-specific modelling, as is presented in this study for the industry sector, cannot stand alone, as many synergy effects and cross-sector interactions cannot be depicted when isolating one specific energy sector. Instead, sector-specific studies, like this study investigating isolated industry sector scenarios, need to be combined with holistic energy system models and analyses, where cross-sector interactions can be considered. This is for example relevant when considering the excess heat potential from industry which could be utilised in e.g., the district heating sector. These cross-sector system effects were not considered in this study, and it is therefore not possible to conclude the effect of the established scenarios outside of the industrial sector.

6. Conclusions

This study can conclude that a transition to 100% renewable energy supply in the European industry is feasible and possible by 2050. Furthermore, it can be concluded, that without extensive implementation of energy efficiency measures, a transition to a 100% renewable industry sector will require large amounts of solid biomass, to such an extent the scenarios are likely unfeasible from a total energy system perspective. In line with the recommendations from the energy efficiency first principle, implementing high amounts of recycling where possible, prioritising the best available technologies for energy efficiency improvements, and electrification of industrial processes to the widest extent possible should be the cornerstone of the industry sector energy transition.

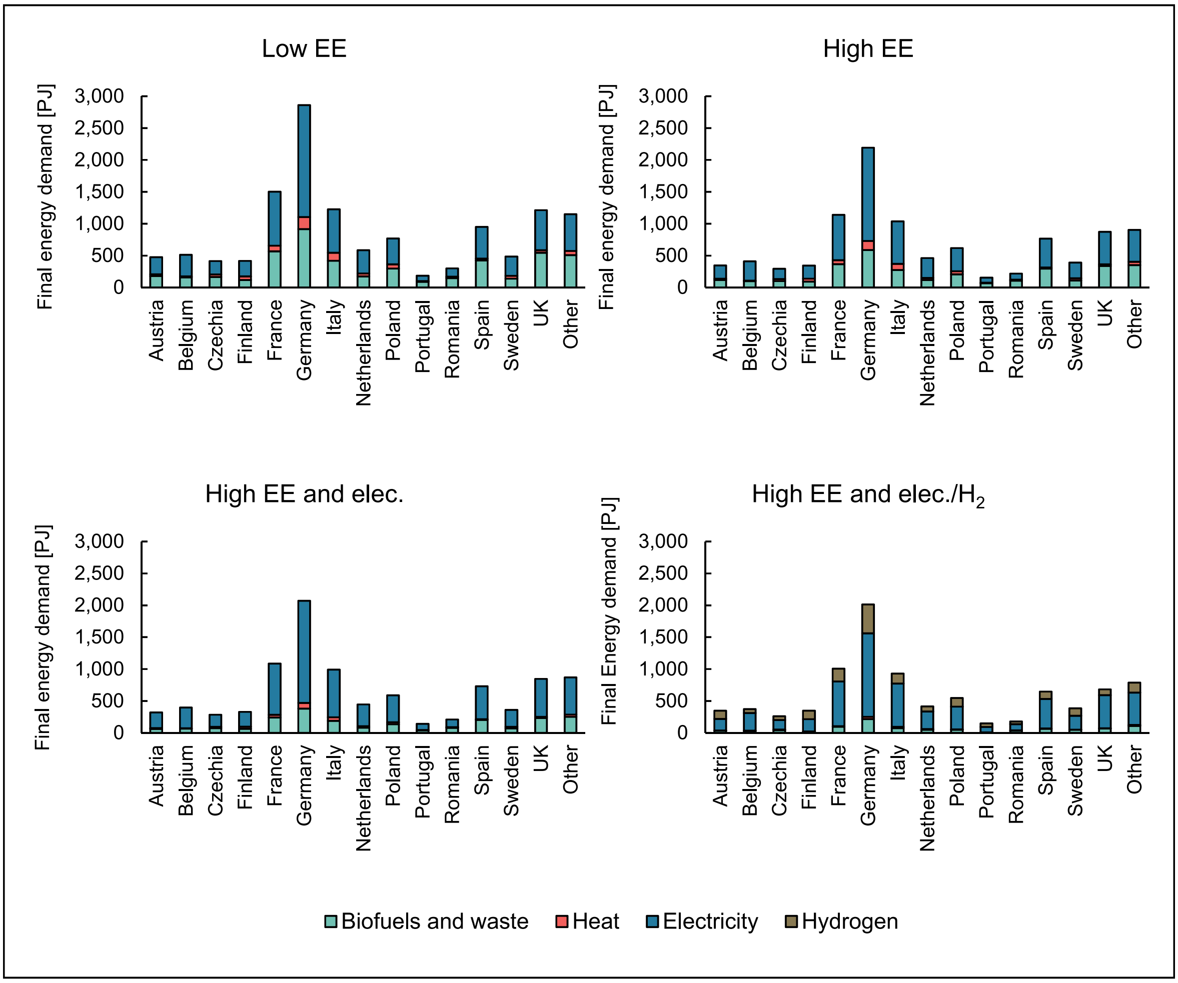

Fig. 13. 2050 country-specific final energy demand distribution per fuel type.

Table 6
Share of energy demands below 200 °C for EU27 + UK.

Sub-sector	2030	2050
Chemicals	14.41%	14.40%
Foundries	0.00%	0.00%
Iron and steel	0.02%	0.03%
Non-ferrous metals	0.00%	0.00%
Non-metallic minerals	12.28%	12.25%
Paper and pulp	93.00%	93.00%
Others	41.00%	41.00%
Total	**29.11%**	**30.00%**

It can furthermore be concluded that a transition to 100% renewable energy in industry calls for additional measures, including innovative technological developments, alongside limited hydrogen-based processes and limited bioenergy fuel shifting measures. Hydrogen and bioenergy should however be strictly prioritised for hard-to-abate processes, found e.g., within the chemicals and iron and steel sub-sectors.

Finally, it can be concluded that the transition of the industry sector can, and should, proceed immediately. Significant potentials for energy savings and CO_2 reductions exist, and much of this potential can even be realised as net profitable, regardless of whether a 3% or 15% discount rate is applied. Therefore, while the complete transition to renewable energy may not be feasible until after 2030, all countries and industry sub-sectors should proceed with the transition immediately.

Credit author statement

Rasmus Magni Johannsen: Conceptualization, Methodology, Formal analysis, Writing – original draft, Writing – review & editing Brian Vad Mathiesen: Conceptualization, Methodology, Writing – review & editing, Supervision Katerina Kermeli: Conceptualization, Methodology, Data curation, Writing – review & editing Wina Crijns-Graus: Conceptualization, Methodology, Writing – review & editing Poul Alberg Østergaard: Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data is included as Appendices and the IndustryPLAN model is available at https://www.energyplan.eu/seenergies/

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.energy.2023.126687.

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