Modelling pathways towards a climate-neutral EU industry sector

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Abstract

To attain climate neutrality by 2050, the European industry must achieve significant reductions in greenhouse gas emissions. The EU's Green Deal with the new 55 % reduction target by 2030 and the 'Fit for 55' package set the frame for the transition. The Fit-For-55 package is accompanied by an impact assessment that includes scenario analyses for the development of the EU energy system until 2030. A perspective Beyond 2030 is not published, but essential to understand the need to achieve climate neutrality by 2050.

Here, we develop two scenarios for the industry sector to benchmark the scenarios published by the EU. We extend our scenarios towards 2050. One scenario reflects current policies (not yet including the proposed fit-for-55 package) and a second scenario that is in line with meeting climate neutrality by 2050 (Mix95). We use the industry-sector simulation model FORECAST. The model calculates energy demand and GHG emissions pathways based on assumptions about policy instruments like CO_2 prices or investment grants with a high technology detail.

Results show that the current policy scenario is not in line with the Green Deal target and is far from reaching climate neutrality by 2050. The Mix95 Scenario achieves ~95 % GHG reduction by 2050. To meet this reduction, various strategies are necessary. A fast and comprehensive switch to electricity and hydrogen is driven by higher CO_2 prices and OPEX support. Driven by the electrification of process heating, electricity demand increases significantly to ~1600 TWh by 2050 starting from 1018 TWh in the year 2018. Also, hydrogen sees a rapid uptake to reach 811 TWh by 2050 prioritizing use in steelmaking and chemical feedstocks. CCS and CCU are used to capture the remaining process emission in the cement and lime production resulting in 75 Mio. t CO_2 captured in 2050. Effective instruments for circularity and material efficiency reduce the production of energy-intensive goods and thereby the demand for CO_2-neutral energy carriers.

Introduction

The goal has indeed been set: in 2020, the EU presented its ambitious 2050 Long-Term Strategy, which increased the previous 2050 target of at least 80 % reduction in GHG emission in comparison to 1990 toward the first climate-neutral continent. The 'fit for 55' legislative package introduced in July 2021 reaffirms the long-term commitment of the EU to climate neutrality by 2050, through introducing measures to reduce the emissions at least 55 % by 2030 relative to 1990 levels, instead of the previous 40 % target (*COM/2021/557*. EUROPEAN COMMISSION, 2021)

In 2019 the industry sector accounted for 26 % of the total final energy consumption (Statistics | Eurostat, 2022) and about 21 % of the GHG emissions corresponding to 775 Mt of CO_2 equivalent (European Environment Agency). Energy-intensive industries such as steel, cement, and basic chemicals constitute a significant part of the economy and are responsible for the majority of the final energy consumption and GHG emissions of the industry sector (Herbst et al., 2021). Most of the GHG emissions are produced from fuel combustion for high-temperature process heat, and a substantial share of emissions is linked to chemical processes. The majority of energy is used for process heating, which is currently mainly provided by fossil fuels. Challenges to converting to a CO_2-neutral industry are manifold. In addition to the high energy intensity and high-temperature levels of processes, solutions to reduce process-related GHG emissions are still in the early stages of technical development.

From 1990 to 2019 the industry sector has significantly reduced the emissions by 35 % through capitalizing on energy efficiency measures and also structural changes in the industry sector (European Environment Agency). Despite the fact that energy efficiency is still essential, it will not be sufficient. For instance, the remaining energy efficiency potential for the German energy-intensive industry is estimated to be about 14 % by 2035 (Fleiter et al., 2013)

Achieving a 55 % reduction by 2030 and climate neutrality by midcentury can only be achieved by going beyond energy efficiency and significantly increasing ambition also in other mitigation strategies including a switch in the energy supply of industry by using low-carbon energy carriers (Rehfeldt et al., 2020), increasing the ambition on circularity, green value chains, product substitution and carbon capture. Setting up a consistent policy framework to meet the long-term goals effectively by accelerating the industrial transition is an enormous challenge for policymakers. Among others, they lack information on the technological pathways and the contribution of different strategies.

Here, we aim to provide more insights via techno-economic modelling of decarbonisation pathways for the EU industry. More specifically, we like to answer the following questions:

- *Where is the transition of the EU industry heading under the current policy framework?*
- *What is a possible pathway towards a CO_2-neutral industry from a techno-economic perspective?*
- *What is the gap between both pathways and which technological strategies are needed to close it?*

Methodology

To address these questions, we use a simulation tool that allows calculating the resulting energy and CO_2 emission pathways of the EU industry sector based on techno-economic assumptions. We define two scenarios and compare results and assumptions. The first scenario reflects the current policy frame (CP) and the second scenario reflects a transition pathway that is in line with a CO_2-neutral EU economy by 2050 (MIX95). This work provides insights into which strategies need to be addressed to attain the strategic goal targets.

For this EU-wide industry scenario assessment, we use the bottom-up model FORECAST. The model represents the whole industry sector with a high level of details including not only energy-intensive processes but also numerous less energy-intensive sub-sectors and applications. The main objective is to define scenarios for the long-term development of energy demand and GHG emissions for the industry.

The input data for the modelling include economic performance per industry, energy and CO_2 prices, assumptions on policy instruments (e.g. investment grants), structural data such as energy and GHG balances, and techno-economic data of the depicted technologies. Statistical data, empirical studies, literature and expert estimates are used for calibration.

For the development of decarbonisation scenarios/paths, a wide range of different decarbonisation strategies can be considered including for example energy efficiency, circular economy and recycling, fuel switch or process switch. Energy efficiency improvements and fuel switching are modelled endogenously on a technology level in several individual sub-models. Mitigation options like material efficiency and recycling are considered via exogenous assumptions that need to be incorporated in the scenario definition. Fleiter et al. provide a more detailed description of the model (Fleiter et al., 2018)

Scenario definitions and assumptions

In this study, we assess two decarbonisation scenarios, a **current policy scenario (CP)** and a **target scenario (MIX95)** that is in line with GHG neutrality in 2050. The scenarios are based on the study (Fleiter et al., 2019) and were updated to reflect the most recent developments, policies and statistics. In particular:

- New economic forecasts are in line with the most recent EU reference scenario (2020) (EUROPEAN COMMISSION et al., 2021). This mainly relates to GDP, industrial gross value added and energy price forecasts.
- Including most recent statistics on energy prices, CO_2 prices, energy and GHG balances, industrial production for main products.
- Updating technology assumptions to the state of the art where better information is available.
- Considering most recent policy developments, such as a strong drive towards supporting the uptake of hydrogen for industrial uses.

The CP scenario aims to capture todays level of policy implementation at the EU level but does not yet include instruments that were proposed or are being discussed within e.g. 'Fit for 55' package. The MIX95 scenario describes a pathway that achieves the long-term goal of at least 95 % GHG reduction by 2050 compared to 1990 for the industry sector. The scenario assumes a strong expansion of policy support and regulation in order to meet this target. It draws on a relatively balanced mix of mitigation strategies including energy and material efficiency, circularity, electrification, hydrogen and clean gas as well as carbon capture and storage (CCS). In the following, we discuss individual assumptions for both scenarios.

The current policy scenario presents a narrative that focuses on ambitious diffusion of today's best available technologies (BAT) for energy efficiency in which Hydrogen is only used to a limited extent in line with the EU Hydrogen Strategy (*COM/2020/301.* EUROPEAN COMMISSION, 2022), while the target scenario (MIX95) capitalizes on a mix of innovative technologies with Technology Readiness Level (TRL) above 4. This implies that technical challenges have been overcome and technology readiness has been demonstrated in pilot plants. Major challenges for the market introduction are upscaling and economics. Furthermore, the target scenario assumes an economic and political framework that ensures the competi-

Table 1. Overview of the major technology assumption by scenario.

Product	Scenario	Process switch	Material strategies	CCS
Steel	CP	52% H-DR share by 2050	High-quality EAF, increase EAF share from 41% (2019) to 64% by 2050, more efficient steel use and substitution result in a decrease in production	-
	MIX95	100% H-DR share by 2050	Same as CP	-
Cement and lime	CP	BAT efficiency	Decrease in the clinker share	-
	MIX95	Low-carbon types of cement enter the market and substitute around 15% by 2050, BAT efficiency,	Ambitious decrease in the clinker share, Efficient concrete use and substitution, concrete recycling and re-use result in a decrease in production	CCS for lime and clinker
Chemicals	CP	BAT efficiency, 40% Feedstock H_2 for Ammonia	A slow increase in plastics recycling	-
	MIX95	100% Feedstock H_2 for Methanol, ethylene and ammonia	A higher increase in plastics recycling, plastics substitution, reduced fertilizer demand and more efficient material use.	-
Glass	CP	BAT energy efficiency	A slow increase in recycling	-
	MIX95	70% Electric furnaces by 2050	Increase flat glass recycling and more efficient glass use	-
Paper	CP	BAT energy efficiency	Ambitious recycling	
	MIX95	Innovative efficiency (paper drying, enzymatic pre-treatment, black liquor gasification)	Ambitious recycling	

tiveness of hydrogen and other synthetic fuels compared to natural gas. Accordingly, hydrogen and methane are produced on a large scale based on electrolysis and renewable electricity. Consequently, it is assumed that relevant production will start after 2025. Carbon capture and storage (CCS) is used only in the MIX95 scenario for the lime and clinker. The scenarios also require more technology-specific assumptions for process switch, CCS and material strategies. These are exogenous inputs to the modelling. *Table 1* shows an overview of the technology-specific assumptions.

It is assumed that the iron and steel industry start to abandon the use of coal as a reducing agent in favour of routes that reduce iron using hydrogen direct reduction (H-DR) of iron with electric arc furnace (EAF). Figure 1 shows the EU28 crude steel production by process and scenario. Furthermore, the chemical industry in the current policy scenario begins transitioning away from fossil-based feedstock toward hydrogen for ammonia production. In the MIX95 all ammonia, ethylene and methanol production switches to hydrogen-based production until 2050.

The scenarios aim to achieve the reduction targets, yet successfully maintain **economic development**, with GDP doubled by 2050 in comparison to the year 2000. (EUROPEAN COMMISSION et al., 2021). Both scenarios, use the same macroeconomic framework data, which is based on the European Reference Scenario 2020. An average annual growth rate in (gross) value added of around 1.6 % p.a. is assumed for the industry until 2030, afterword's the growth rate declines to 0.6 % p.a. The equipment goods industry (engineering) is projected to be growing at a steady higher pace compared to the energy-intensive basic industries. In addition, in the long run, a moderate decoupling of the value-added and the physical production volumes in the basic industry are projected.

Based on the assumptions for economic development in terms of value-added per sector, we derive assumptions on **future production of major energy-intensive products**. Considering the physical production of more than 50 energy-intensive products on a country level is a major strength of our modelling approach and allows us to develop pathway scenarios with a high level of technology and process detail (see for more details (Fleiter et al., 2018)). Here, we discuss assumptions for major products that strongly affect results. Besides economic development, also changes in material use and efficiency along the value chain can

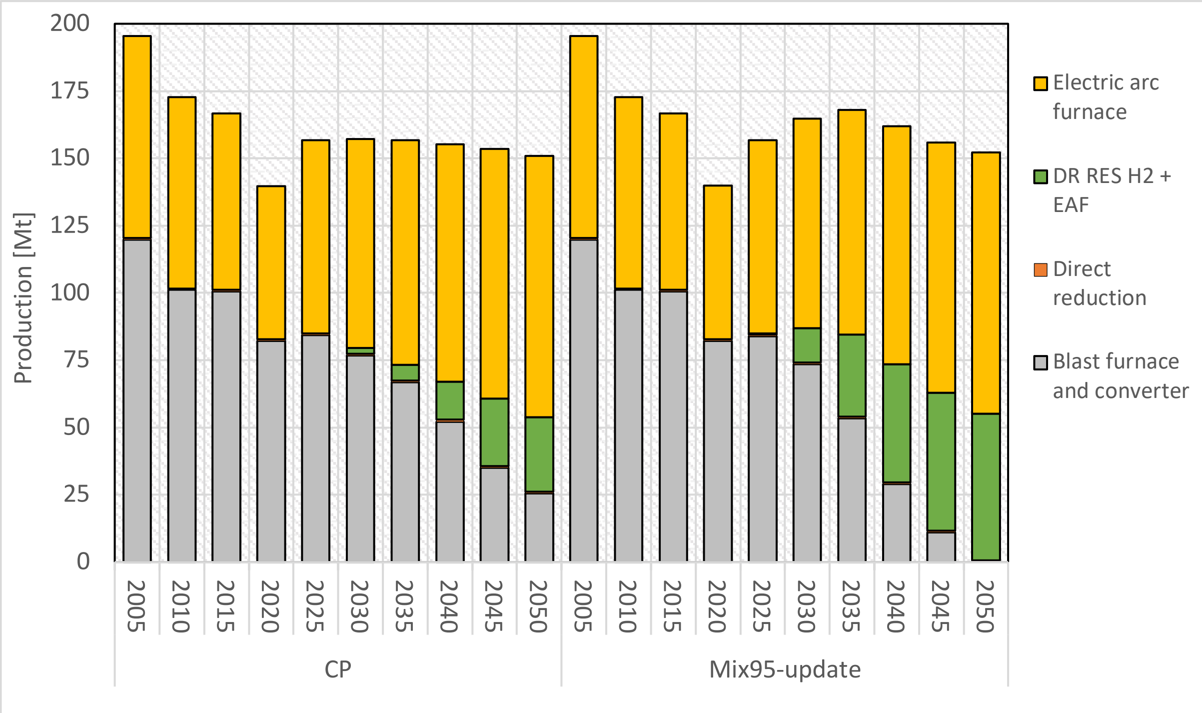

Figure 1. EU 28 crude steel production by process and scenario.

change the demand and production of basic material products. We have assumed such improvements, particularly in the MIX95 scenario reflecting a transition also at the demand side.

The assumption of increased material efficiency along the value chain results in a slight decrease in steel tonne production in the long run. Steel demand slightly decreases as a result of material efficiency improvement, material substitution, re-use and behavioural changes. The total cement increases in the CP scenario, this increase mainly takes place in the period from 2020 to 2030 driven by developments in the construction sector. In the MIX95 the cement production decreases starting from 2030 this decrease is driven by material efficiency and substitution in the construction sector where potentials for more efficient concrete use are large. Products such as flat glass and aluminium show a rather constant development. The change in the production is summarized in Table 2.

In the CP scenario, the CO_2 price for the EU ETS is at around €50/tCO2-eq in 2030, €100/tCO2-eq in 2040 and €200/tCO2-eq in 2050. The MIX95 assumes a higher CO_2 price for the EU ETS: around €110/tCO2-eq in 2030, €210/tCO2-eq in 2040 and €490/tCO2-eq in 2050). In the MIX95 scenario, we assume in addition also a CO_2 price for the non-ETS industry sector. This is needed to drive fuel switch towards low-carbon energy carriers in the less energy-intensive industries like machinery, food and others.

Results

GHG EMISSION

This section summarises and discusses the main findings of this work. This study considers the direct energy- and process-related GHG emissions within the scope of the industry sector. This includes also selected non-CO_2 sources like e.g. N_2O emissions from adipic acid and nitric acid production. Upstream emissions from e.g. electricity generation are not accounted for. This is consistent with the EU's GHG monitoring and target definition.

The result of the CP scenario shows that the EU27 industry fails to achieve the GHG emissions target announced in the EU Green Deal, emitting 619 Mt CO_2-eq by 2030. Compared to 1990 the industrial GHG emissions in the CP scenario are reduced by 47 % and 66 % by 2030 and 2050 respectively. On the other hand, in the Mix95 scenario, the industrial GHG emission decreases to 502 Mt CO_2-eq, representing a 57 % and 94 % decrease by 2030 and 2050 compared to 1990, which is consistent with the EU Green Deal. Figure 3 shows the development of total GHG emissions by sources.

With regard to process-related emissions, in the CP scenario the GHG emissions decrease by 29 % and 46 % by 2030 and 2050 respectively. While in the process-related emissions decreases by 33 % and 66 % by 2030 and 2050 respectively. The slow reduction of process-related emissions in the CP scenario is explained by the fact that they are dominated by the production of non-metallic minerals, e.g. clinker/cement or lime, which is not assumed to change substantially. In the MIX95, fundamental changes in process technologies are taking place (e.g. the introduction of low carbon cement sorts and the reduction of the clinker-share in cement production) which lead to significantly lower process emissions starting from 2030 and thus achieving an overall reduction of 94 % by 2050.

The use of carbon capture and storage (CCS) in the ambitious Policy MIX95 scenario is a significant difference between the two scenarios. The result shows a moderate diffusion of CCS technology only in the Non-metallic mineral products, particularly in lime burning since alternative mitigation options are currently unavailable. Accordingly, the 75 Mt CO_2-eq. are captured by 2050 in the MIX95 scenario.

Table 2. EU 28 Assumed production output of selected basic material products in Mt by scenario (2019-2050).

Product	Scenario	2019	2030	2040	2050	Δ% 2019-2050
Crude Steel	CP	158	158	157	152	-4%
	MIX95	158	158	157	152	-4%
Cement	CP	174	194	199	198	12%
	MIX95	174	182	175	162	-7%
Ethylene	CP	24	25	26	27	15%
	MIX95	24	23	22	21	-6%
Ammonia	CP	17.8	18.2	18.7	19.2	8.1%
	MIX95	17.8	18.2	18.7	19.1	7.5%
Container glass	CP	41	43	42	42	1%
	MIX95	41	42	41	39	-3%
Paper	CP	95	100	102	102	7%
	MIX95	95	100	102	102	7%

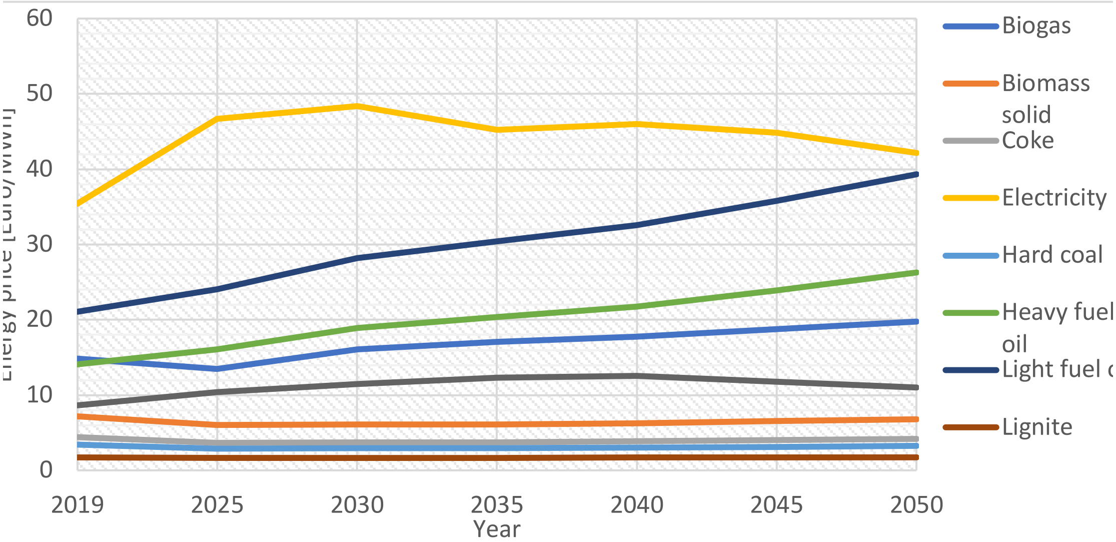

Figure 2. Energy carriers price projections (2019 based Eurostat projection own assumption taking into consideration the EU Reference Scenario 2020 and limited recovery scenario).

FINAL ENERGY DEMAND

Here, we provide some analysis of the industrial final energy demand. As seen in Figure 4 starting from 2030 both scenarios show a steady decrease in the Final Energy Demand (FED). For example, in the CP scenario, the FED decreases by 14 % from 3051 TWh in 2018 to 2616 TWh in 2050. In the MIX95 scenario, final energy consumption decreases by 24 % to 2324 TWh by 2050. This decrease is driven by efficiency improvements and the use of BAT.

The direct and indirect electrification of final energy demand is a persisting trend in both scenarios. The share of direct electricity in total final demand reaches 41 % and 65 % in the current policy scenario and the MIX95 scenario by 2050, respectively (compared to only 31 % in 2018). The demand for natural gas decreases significantly over the projection period; however, it remains a significant energy source. The natural gas demand drops from 876 TWh in 2018 to 481 TWh in the CP. In the MIX95 scenario, it is 100 % replaced with synthetic methane by 2050. The coal consumption falls rapidly in the MIX95 scenario, nearly halving by 2030, compared to 2018 and phased out by 2050. Biomass shows an increase, particularly in the current policy scenario, it almost doubles to 479 TWh by 2050 making biomass one of the most important energy carriers, which is a substantially stronger increase than in the MIX95 scenario. The strong increase in biomass is driven by an increase in the price of CO_2. At these price levels, solutions like hydrogen and (to less extent) direct electrification is not yet cost-effective, so biomass gains large market shares, as possible (domestic and international) limitations to biomass supply are not considered in this scenario.

In this work, we distinguish between two types of electricity demand. The Direct use of electricity as final energy mainly for mechanical energy and heating and the indirect use via electrolysis-based secondary energy carrier's hydrogen (PtH_2) and synthetic methane (PtG). In Both scenarios, the direct use of electricity where possible is preferred over indirect use. The efficiency gains obtained by implementing BAT resulted in reducing the electricity for example in the CP scenario the

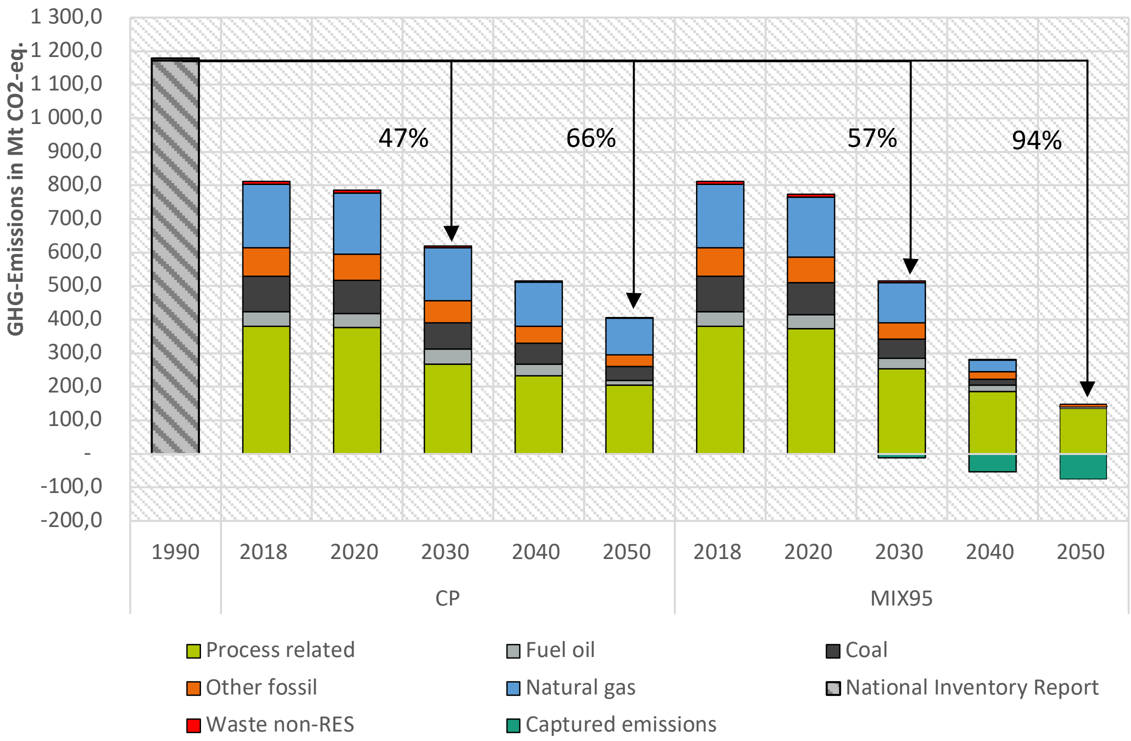

Figure 3. Development of GHG emissions by scenario (EU27, 2018–2050) Forecast.

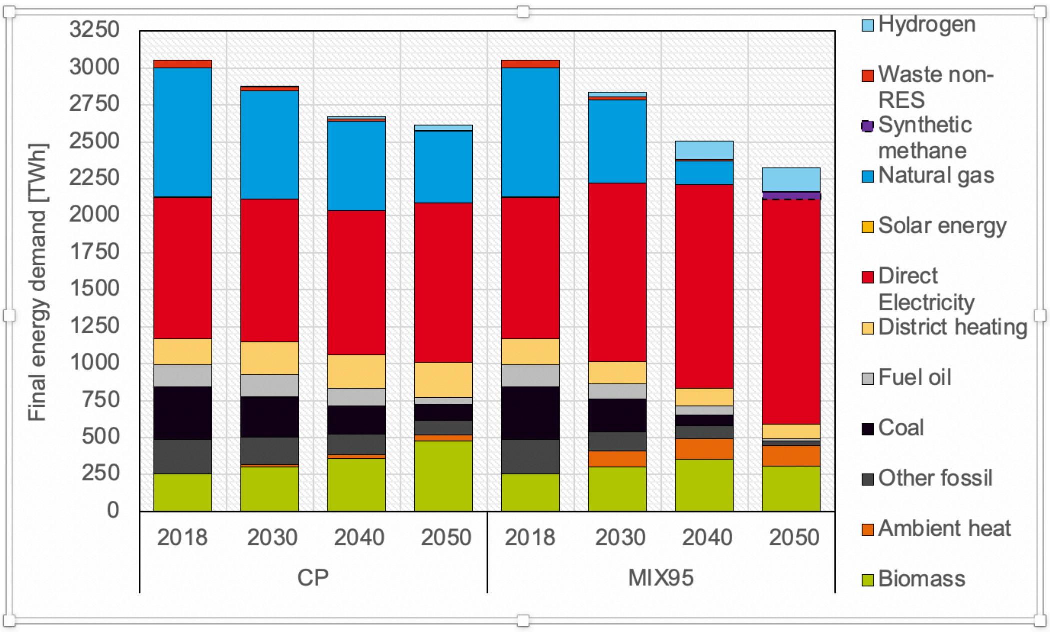

Figure 4. Development of final energy demand excluding feedstocks (EU27, 2018–2050) Forecast.

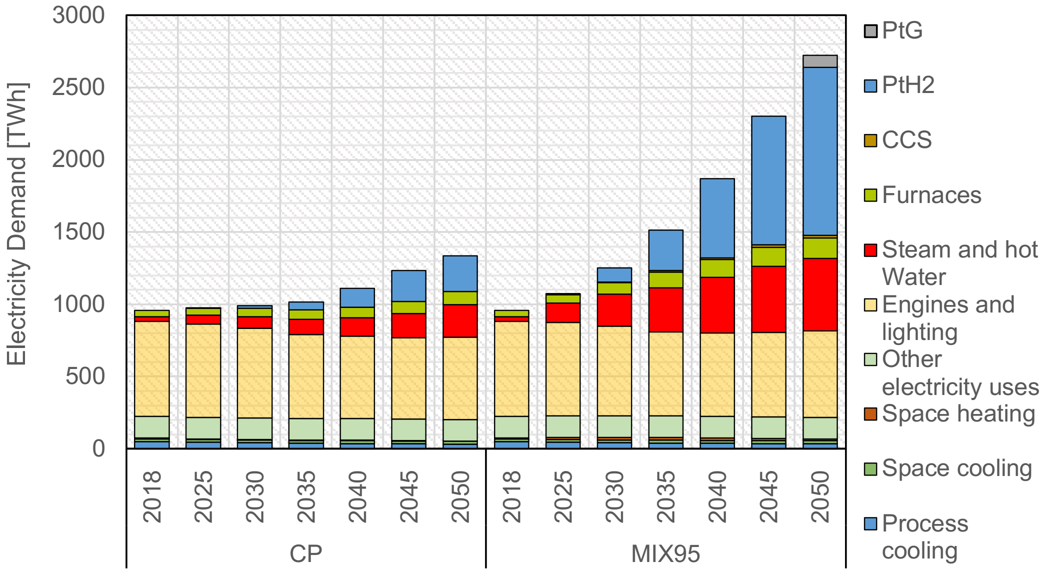

Figure 5. The resulting electricity demand for the industry including the electricity needed for production of hydrogen for the Feedstock (EU27, 2018–2050) Forecast.

electricity demand for process cooling decreased by 37 % and for engines and lighting by 14 %. Nonetheless, in the CP the electricity demand increases by 13 % from 958 TWh in 2018 to 1082 TWh by 2050. As seen in Figure 5 this increase is mainly driven by the electrification of steam and hot water generation.

The MIX95 illustrated substantially higher electricity demand starting from 2030, the direct use of electricity increases to 1521 TWh by 2050, which is an increase of 59 % compared to 2018. The increase is more drastically if also the potential electricity used to produce hydrogen and other e-gases is included, which results in potentially 2768 TWh of electricity demand by 2050. This +186 % increase compared to 2018 is driven mainly by the large-scale use for process heating (567 TWh) as well as the use of hydrogen as feedstocks in the chemical industry (888 TWh), including 194 TWh for the switch to H-DR steel and 490 TWh for and synthetic methane. It shall be noted, though, that not all hydrogen will be produced via electrolysis within Europe. Also, imports might play a role. Anyhow, the increase shows how the transition to a CO_2-neutral industry depends on drastically increased electricity demand. A deeper analysis of the source of hydrogen, however, is outside the industry sector scope of this paper.

Figure 6 compares the market diffusion of hydrogen in both scenarios by end uses. In the MIX95 scenario, hydrogen-based production technologies enter the market in the steel and chemical industry resulting in 68 TWh by 2030, and increases to 813 TWh by 2050. In both scenarios, hydrogen is used as feedstock for the production of ammonia (NH3). Hydrogen dominates the feedstock supply of the chemical industry in the MIX95 scenario. As result, ethylene production in the MIX95 scenario switches to hydrogen-based methanol route resulting in approximately 343 TWh hydrogen demand. Furthermore, the iron and steel industry demand for hydrogen will almost reach 116 TWh in 2050 (both in terms of energy and feedstocks).

Table 3 directly compares the result of this study with the result of the previously reported finding. Direct electrification is a key element in meeting the long term GHG emission reduction target. All the decarbonisation scenarios show a significant increase in the share of electricity in the final energy demand. The CP policy scenario shows a higher GHG emission reduction and higher electricity demand compared to the EU Ref 2020. Carbon-neutral hydrogen and synthetic fuels are used in all scenarios nonetheless an appropriate direct comparison between scenarios is not possible due to the lack of sufficient data.

Conclusion and discussion

In this paper, we develop and compare two EU climate and energy scenarios that take into account many decarbonisation strategies. In the current policy scenario (CP), we assume the use of Best Available Technology in terms of energy efficiency, a continuation of current trends in recycling and limited fuel switch driven by the assumptions on cost and prices resulting in a slow reduction in GHG emissions. This reduction is not in line with the Green Deal target of 55 % reduction by 2030 and is far from reaching climate neutrality by 2050, it does, however also not yet include the instruments of the fit-for-55 package. Among others, a major reason for the gap is that the economic framework (CO_2 price and energy prices) is not sufficient to provide incentives for investing in innovative CO_2-neutral production technologies. Particularly the high OPEX of CO_2-neutral technologies like hydrogen-based steelmaking or electrification of process heat prevents a substantial diffusion in the current policy scenario. In addition, also the transition to a circular economy is not as comprehensive as needed.

In the target scenario MIX95, we included more ambitious assumptions on innovative low-carbon production technologies and strategies such as hydrogen-based chemicals and steel, CCS, comprehensive circular economy and increased material efficiency along the value chain. The MIX95 scenario reaches 94 % GHG reduction by 2050 compared to 1990 and thus is in line with a CO2-neutral economy assuming that some remaining process emissions in the industry will need to be compensated by other measures/negative emission technology.

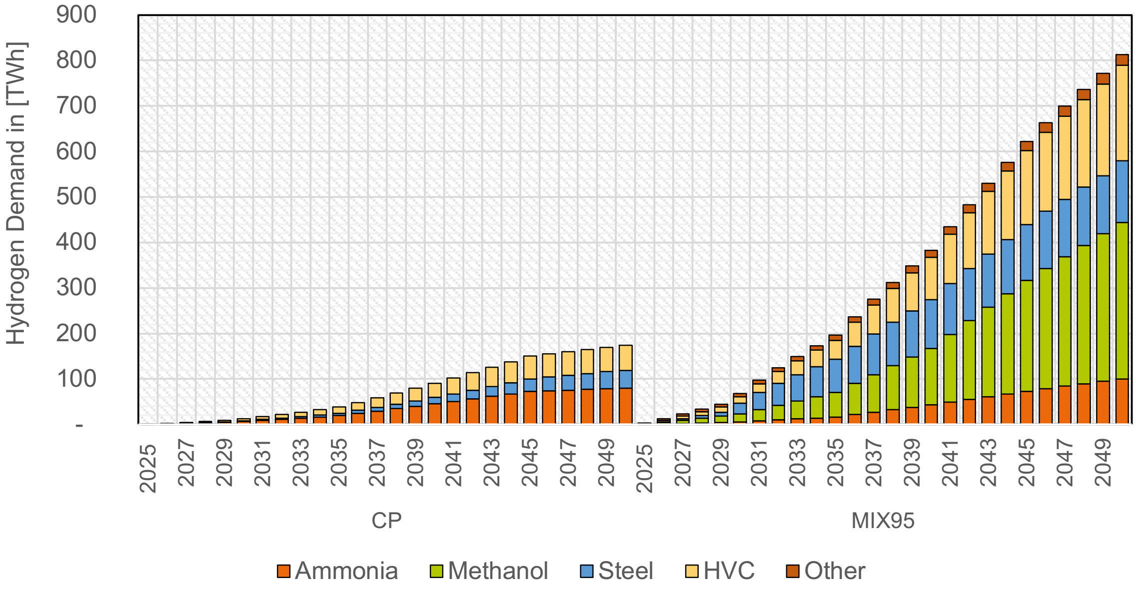

Figure 6. Hydrogen demand by end-use (EU27, 2025–2050) Forecast.

Table 3. EU result comparison * for the MIX95 result are only available unit 2030.

	CP (FORECAST)	EU Reference Scenario 2020 (Primes)	MIX95 (FORECAST)	EU Green Deal scenario MIX* (Primes)
Industry value-added growth pa	1.3%	1.30 % P.a	1.3%	1.81% P.a *
All sectors GHG reduction 2030	-	45%	-	55%
All sectors GHG reduction 2050	-	59.4%	-	-
Industrial GHG reduction 2030 compared to 2015	-12%	-10%	-29%	-23%
Industrial GHG reduction 2050 compared to 2015	-46%	-40%	-93%	-
Final energy demand	-	2030 = 2624 TWh 2050 = 2438 TWh	-	2030 =2458 TWh
Industry Electricity demand 2030	967 TWh	918 TWh	1206 TWh	-
Industry Electricity demand 2050	1082TWh	1024 TWh	1521 TWh	-
Industry Hydrogen demand 2030	13 TWh	-	176 TWh	-
Industry Hydrogen demand 2050	63TWh	-	811TWh	-

The MIX95 scenario relies on an extensive availability of green hydrogen supply, mainly for feedstock but also to some extent for process heat, which results in a demand of 811 TWh in 2050. Direct electrification of heat process where possible results in increasing the demand for electricity by 643 TWh, (this is almost double the 2018 Italian electricity production). CCS and CCU are used to capture the remaining process-related emissions in the cement and lime production resulting in 75 Mio. t CO_2 captured in 2050.

Circular economy will play a major role for products like steel or ethylene. No one silver bullet will result in achieving the climate GHG emission reduction target. A combination of various strategies is needed to achieve the GHG target, which will require a fundamental change in the value chain and industrial energy supply and demand. Many of the innovative low-carbon technologies investigated in this study are in the final stages of development (TRL 5–9). Hence, scaling these technologies and developing relevant strategic infrastructure for electricity, hydrogen, CO_2 transport and storage will be crucial for the decarbonisation. Comparing the current policy scenario with the MIX95 reveals recommendations for policy strategies to make the transition to a CO_2-neutral industry possible. Among others, this includes:

- The cost-effective supply with CO_2-neutral secondary energy carriers like electricity and hydrogen is a central prerequisite for the transformation of the industry sector towards CO_2 neutrality.
- Especially hydrogen-based production technologies are not yet cost-effective under current CO_2 and energy prices.

Further financial support schemes will be needed to assure market diffusion will not start too late, e.g. for hydrogen-based DRI

- Electrification of process heating is an efficient strategy to decarbonize large parts of the industry sector, however, to roll it out soon, OPEX support or lower electricity prices are required in most countries
- CCS is needed to store remaining CO_2 emissions from processes in the cement and lime industries. Here, the regulatory frame, as well as infrastructure for transport and storage, are not yet well developed.
- Circularity and material efficiency require effective policy instruments to enable large-scale emission savings. In particular, the switch to secondary steel, but also recycling routes in plastics production have large potential.

A comprehensive assessment of the whole energy system and sector coupling is an important next step for further research.

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