European Commission

METIS 3- Study S5

The impact of industry transition on a CO_2-neutral European energy system

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Abbreviations

Abbreviation	Definition
BAT	Best Available Technology
CCGT	Combined-Cycle Gas Turbine
CCGR CCS	Combined-Cycle Gas Turbines with Carbon Capture and Storage
CCS	Carbon Capture And Storage
CSC	Conventional Steam Cracker
CHP	Combined Heat and Power
EAF	Electrical Arc Furnace
ESC	Electrical Steam Cracker
FED	Final Energy Demand
FLH	Full-Load Hours
GVA	Gross Value Added
GHG	Greenhouse Gas
H2-DRI	Hydrogen Direct Reduction
HBI	Hot Briquetted Iron
HVC	High-Value Chemicals
LTS	Long-Term Strategy
MTO	Methanol To Olefins
NG	Natural Gas
PV	Photovoltaics
RES	Renewable Energy Sources
TED	Total Energy Demand
TYNDP	Ten Years Network Development Plan

Metis configuration

The configuration of the METIS model used to evaluate the impacts of the scenarios s is summarised in Table 1.

Table 1 - METIS Configuration

METIS Configuration	
Version	METIS v2.0 Beta (non-published)
Modules	Energy system integration module
Scenario	METIS 2050 scenario
Time resolution	Hourly (8760 consecutive time steps per year)
Spatial granularity	Member State

1 INTRODUCTION

In Europe, approximately 20% of the total Greenhouse Gas (GHG) emissions can be attributed to the industry sector. The primary contributors to GHG emissions within the industry sector are associated with the production of basic materials in sectors such as steel, cement, and chemicals. Although this sector has been regarded as "hard-to-abate" for a long time, there is now a growing consensus that industry holds significant potentials for greenhouse gas reduction by switching to new low-carbon production routes and technologies. These include the direct use of electricity from renewable sources or its indirect use through hydrogen or synthetic methane, but also carbon capture and storage, improved energy efficiency or a more stringent roll-out of the circular economy and material-efficient value chains Fleiter et al. (2019a).

The EU's long-term strategy "A Clean Planet for All", published in 2018, outlines the vision of achieving climate neutrality in the EU and explores concrete transition pathways for the entire economy. It shows that making full use of the available mitigation options enables the industry sector in the EU to decarbonise by up to 95% by 2050 compared to 1990[1].The accompanying Staff Working Document explores alternative decarbonisation pathways and ambition levels[2]. Among these is a 95% reduction scenario for the industry sector, which shows a tripling of the electricity demand in the industry sector from about 1000 TWh today to about 3000 TWh in 2050. This implies deep changes on both the supply and demand side and strong interactions between the industry sector and the energy system. With the Green Deal, the EU has adopted an ambitious target to become the first climate-neutral continent by 2050[3]. The Fit-for-55 package and RePowerEU plan form the frame for the implementation of multiple instruments and measures to achieve this target.

Deep decarbonisation of EU industry is possible without de-industrialisation, although which technology pathway industry will and should take is still being debated. In all deep decarbonisation pathways, however, sector coupling plays a very important role, as fossil fuels are replaced by large quantities of CO_2-neutral secondary energy carriers like electricity, hydrogen or synthetic fuels. Consequently, an overall system perspective is required to assess transformation pathways comprehensively. At the same time, transformation pathways will differ across the various sub-sectors of the basic materials industries. Each sub-sector uses specific production processes and consequently has different potentials and limitations to apply CO_2-neutral technologies. Some production

[1] EUROPEAN COMMISSION 2018a.

[2] EUROPEAN COMMISSION 2018b.

[3] EUROPEAN COMMISSION.

processes require large-scale re-investment, while for others retrofitting will be possible. Furthermore, industrial transformation is likely to vary significantly between different regions due to the influence of location-specific characteristics such as Renewable Energy Sources (RES) potentials and infrastructure availability. Therefore, a methodology to model the transition of the industry sector needs to take into account the energy system, industrial structures and sub-sector-specific production processes with their respective technology limitations.

Against this background, this study analyses two main mitigation pathways – the electrification and the hydrogen pathway, and assesses their potential impacts on the energy system. The study applies an EU-wide energy system model together with a dedicated industry sector simulation model to capture both the energy system effects and the industry-specific potentials and limitations for transition.

2 OBJECTIVE, METHOD AND OVERVIEW OF SCENARIOS

The main objective of this study is to gain deeper insights into possible pathways for industry decarbonisation, their resulting energy demands and the impact on the overall European energy system.

The model set-up and workflow is illustrated in Figure 1. The method uses the **METIS energy system model**, which is able to optimise the European energy system as a whole including the deployment of supply options, electricity and hydrogen transport grids and dispatch at hourly resolution. We apply the METIS model to a CO_2-neutral target system in the year 2050. In order to have a high level of detail for the industry sector, we first use the **simulation model FORECAST** to calculate transition pathways for the industry sector. The FORECAST model considers a high level of technology and process detail for the basic materials industries and can calculate the resulting energy demands Fleiter et al.(2018) and Rehfeldt et al. (2020). These resulting energy demands are then fed into the METIS model to calculate the impact on the overall energy system. Within the METIS 3 project, a framework to link FORECAST with METIS was established and validated. Framework data and assumptions like industrial growth, energy or CO_2 prices as well as energy demand for the sectors of transport and buildings are taken from the EU's Mix-H2 scenario.

Model Set-up

1. Primes Mix-H2 scenario as basis for framework data and energy demand of transport and buildings sectors

2. FORECAST-Industry to calculate detailed scenarios for industry transition and required energy demands

3. METIS to optimize supply system based on energy demand from FORECAST for industry and Mix-H2 for other sectors

Figure 1: Overview of workflow and model system

In order to understand the consequences of alternative transformation pathways in the industry sector, we defined two main scenarios and two sensitivities as shown in Figure 2. The scenarios, **Elec+** and **H2+,** focus on the competition between hydrogen and electrification as two main strategies for achieving a CO_2-neutral industrial system. In many industries, it is not yet certain which of these two options will play the major role in decarbonisation. At the same time, these options imply huge potential demand for hydrogen or electricity, affect the overall energy system, and have very different infrastructure needs. Another main uncertainty regarding industry transition stems from potential changes in global value chains. We capture this in the sensitivity analysis **Elec+_VC**, which assumes that basic chemicals like ethylene or ammonia and iron sponge are no longer produced in Europe, but imported. Given the huge energy demand associated with these products, this would have a major impact on the energy system. Both main scenarios require very ambitious deployment of Renewable Energy Sources (RES) in most EU countries. To capture the uncertainty regarding the implementation and speed of RES deployment, we also defined the sensitivity analysis **H2+_LimPotential,** which limits the available potentials of wind and solar energy.

Definition of scenarios

Scenario H2+ (Focus hydrogen): Hydrogen is the major decarbonisation option for feedstocks and process heat, although electrification also plays a role in process heat, especially where lower temperatures are involved.

> **Sensitivity H2+_lim.Potential** (Supply side, limited renewable potentials): Only 70% of wind and solar potentials available, with 20% minimum deployment of rooftop PV

Scenario Elec+ (Focus electrification): Electrification plays a greater role in the decarbonisation of process heat if technically mature (TRL of at least 5.

> **Sensitivity Elec+_VC** (Industry sector, new global value chains): Import of sponge iron, ammonia and green ethylene and other HVCs, everything else remains as in the Elec+ scenario. Substantially lower hydrogen demand

Figure 2 Overview of scenarios and sensitivity analyses

Table 2 provides an overview of the main assumptions and differences between the scenarios and sensitivity analyses. The study compares two deep decarbonisation scenarios, **Elec+** and **H2+**, which differ primarily in the energy supply technologies used to achieve the GHG reduction target. Both scenarios aim to achieve a short- and long-term GHG reduction target of at least 55% and 95% by 2030 and 2050, respectively compared to 1990. This reduction target is compatible with GHG neutrality in 2050, as long as negative emissions are achieved in other sectors. The H2+ scenario focuses on hydrogen as a major decarbonisation option for feedstocks and process heating. However, where it is substantially more efficient, electrification will also play a role, for example, via high-temperature heat pumps to produce hot water and steam. Thus, the H2+ scenario does not represent an "extreme" hydrogen world, but a future pathway that relies strongly on hydrogen as a central decarbonisation option for industry. In contrast, the Elec+ scenario focuses on electrification as the major decarbonisation option, especially for process heat where this is technically mature. However, this scenario also features CO_2-neutral hydrogen and represents a diverse supply mix with an emphasis on electrification.

Two sensitivity analyses evaluate the robustness of the solutions, with **H2+_LimPotential** focusing on the supply side and **Elec+_VC** on the demand side. In the H2+_LimPotential, the sensitivity analysis provides insights into the uncertainties concerning RES potential and expansion. The RES potential for utility-scale photovoltaic (PV) and wind is limited to

70% of the technical potential. In addition, PV rooftop deployment per Member State is assumed to be at least 20% of the technical potential. This sensitivity is based on the H2+ scenario and changes are only introduced to the energy supply side. In the Elec+_VC, value chains are changed as energy-intensive processes for selected products are relocated outside of the EU in regions with higher RES potential.

In the following section, we provide a brief description of the two models used for the analysis. Chapter 3 then reports the assumptions and results for the industry sector modelling, while chapter 4 focuses on the assumptions and results concerning the use of METIS to model the overall European energy system.

Table 2: Overview of the main assumptions

	H2+	H2+_LimPotential	Elec+	Elec+_VC
GHG target 2050	At least 95% GHG reduction compared to 1990 for the industry (in line with overall GHG neutrality)			
GHG target 2030	Reduction similar to Primes Mix-H2 scenario in line with overall 55% GHG reduction target			
Economic growth	Continued long-term growth of industry GVA ~0.8%, recovery from Covid-crisis with higher growth before 2030			
Biomass	No particularly strong role / limited use of biomass			
Energy and material efficiency and circular economy	Ambitious progress			
CCS and CCU	Included for cement and lime plants only			
Process, fuel and feedstock switch	Priority hydrogen		Priority electrification	
Renewable energy potential	Technical potential	Limited technical potential	Technical potential	
Relocation of basic materials plants	Domestic production of green basic materials at today's locations			Import of sponge iron, green ammonia and HVCs

The FORECAST industry sector model

FORECAST-Industry is a bottom-up simulation model designed to analyse the long-term development of energy demand and emissions for industry. The model considers a broad range of mitigation strategies with a high level of technological detail at the process level. The main strategies are energy efficiency improvements, switching to new low-carbon processes, switching to renewable and low-carbon energy carriers, carbon capture and storage (CCS), as well as circular economy and recycling, material efficiency and substitution along the value chain. Moreover, the model takes into account macroeconomic trends, energy prices and policy frameworks such as CO_2 prices, standards, grants and support schemes for low-carbon solutions as well as changes in consumer behaviour. FORECAST-Industry also explicitly considers technology diffusion and stock turnover; this allows insights into the adoption of new technologies and their impact on the sector's energy demand and emissions over time. This level of detail provides policymakers, industry stakeholders and researchers with the relevant information and insights needed to make informed decisions about energy efficiency, technology development, and investment strategies in the industrial sector.

The scope of the model is defined by the energy balances. These cover major energy-intensive processes with a high level of detail as well as many less energy-intensive sub-sectors and applications, and include energy balances, employment, value-added, and energy prices, which are calibrated to the most recent EUROSTAT statistics if available. The model requires a broad set of input data and combines a variety of data sources. The model database was first developed in 2008 by Fraunhofer ISI and since then has been continuously expanded and enhanced to reflect the most recent developments, policies and statistics. For a more detailed model description, we refer to Fleiter et al.(2018) and Rehfeldt et al. (2020)

The METIS energy system model

The METIS[4] energy system model is being developed by Artelys on behalf of the European Commission. METIS is a multi-energy model with high granularity (in time and technological detail) that covers the entire European energy system by representing each Member State of the EU and relevant neighbouring countries as a single node.

METIS has its own modelling assumptions and datasets and comes with a set of pre-configured scenarios. These scenarios usually rely (at least partially) on the inputs and results from the European Commission's projections of the energy system, for instance with respect to the capacity mix (for selected technologies, others being subject to capacity optimisation) or annual demand. Based on this information, METIS performs the hourly capacity expansion and dispatch optimisation over an entire year, i.e., for 8760 consecutive time-steps per year. The result consists of the capacity mix and the hourly utilisation of all

[4] See https://energy.ec.europa.eu/data-and-analysis/energy-modelling/metis_en

national generation, storage, conversion and cross-border capacities as well as demand-side response assets.

3 INDUSTRY SECTOR ANALYSIS

This chapter reports the assumptions and results of the industry sector modelling for the defined scenarios and sensitivities. While the entire industry sector is modelled according to its definition in the energy balances, including non-energetic use for feedstocks, we will go more into detail for the basic materials industries, due to their relevance in terms of CO_2 emissions and energy demand.

3.1 ASSUMPTIONS

The main assumptions for the FORECAST industry sector model comprise projections of macroeconomic variables like the value added per industrial sub-sector or the physical production of major energy-intensive products as well as energy and CO_2 prices, but also more sector-specific techno-economic assumptions like the increase in the share of secondary production or material efficiency potentials. The following sections summarise the main assumptions with a particular focus on sectors with the highest CO_2 emissions and energy demand: Iron and steel and the chemical industry. However, FORECAST also considers other energy-intensive sectors in depth and captures the entire energy demand of the industry sector.

3.1.1 INDUSTRIAL VALUE ADDED AND PRODUCTION OUTPUT

The scenarios aim to achieve the reduction targets, while maintaining economic development. By 2050, the EU27+ UK's Gross Value Added (GVA) will have increased by 150% compared to the year 2020. The GVA by sub-sector is the main macroeconomic driver for the production volumes of important energy-intensive products in the scenarios. All the scenarios in this study use the same macroeconomic framework data based on the European MIX-H2 Scenario 2020 (EUROPEAN COMMISSION 7/14/2021). An average annual growth rate of around 1.3 % p.a. is assumed for the GVA in industry until 2030, which then declines to 0.7%% p.a. The *Machinery and equipment* industry (engineering) is projected to grow at a constant higher pace than the energy-intensive basic industries as shown in

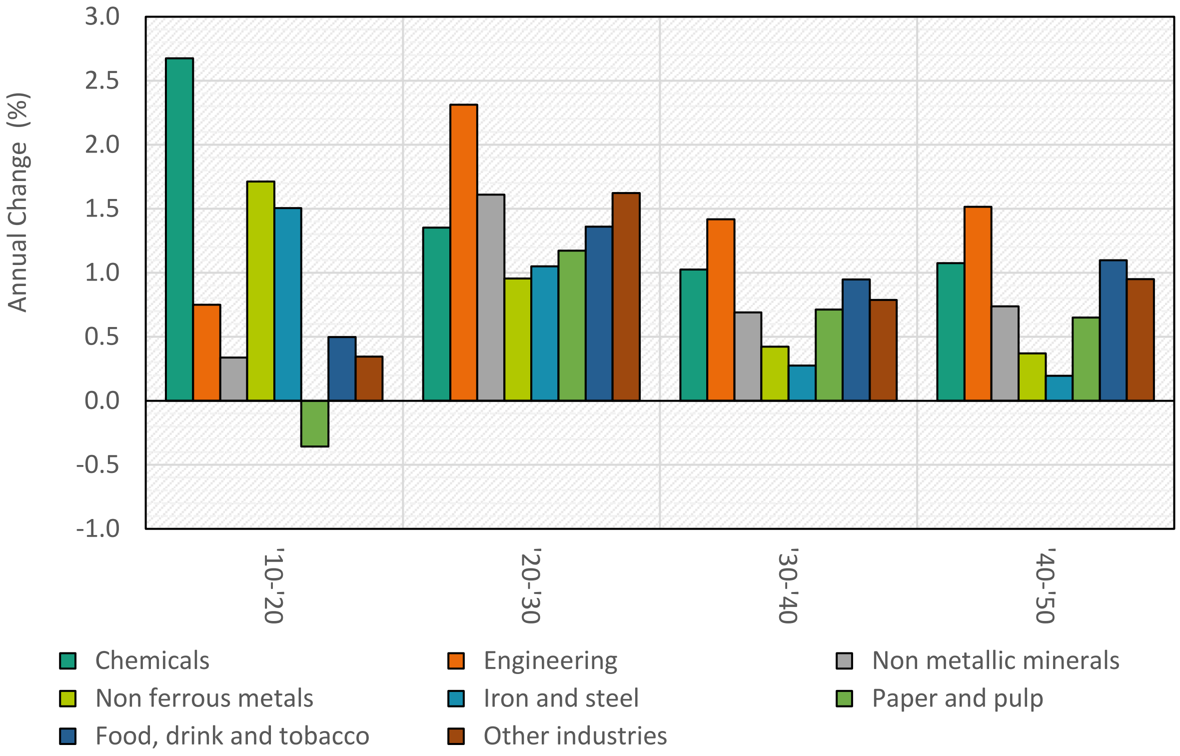

Figure 3: EU27 average annual growth rate in industrial gross value added by sub-sector (2010-2050)

The future production of major energy-intensive products is derived based on economic development assumptions in terms of GVA per sector and assumptions about material use and efficiency along the value chain. In this context, a gradual decoupling of GVA and physical production outputs in basic industries is projected in the long term. Furthermore, an increase in material efficiency along the value chain is assumed due to technological advancements and process innovations as well as re-use and behavioural changes. As a result, in contrast to the development of sub-sector GVA, a slight decrease is projected for some products. For instance, the production of cement and steel is projected to reach saturation and then slowly decrease from 2030 onwards. On the other hand, products such as flat glass, paper, and aluminium are relatively constant. Figure 4 shows the projection for the EU 27+ UK production of selected GHG-intensive products in primary industries.

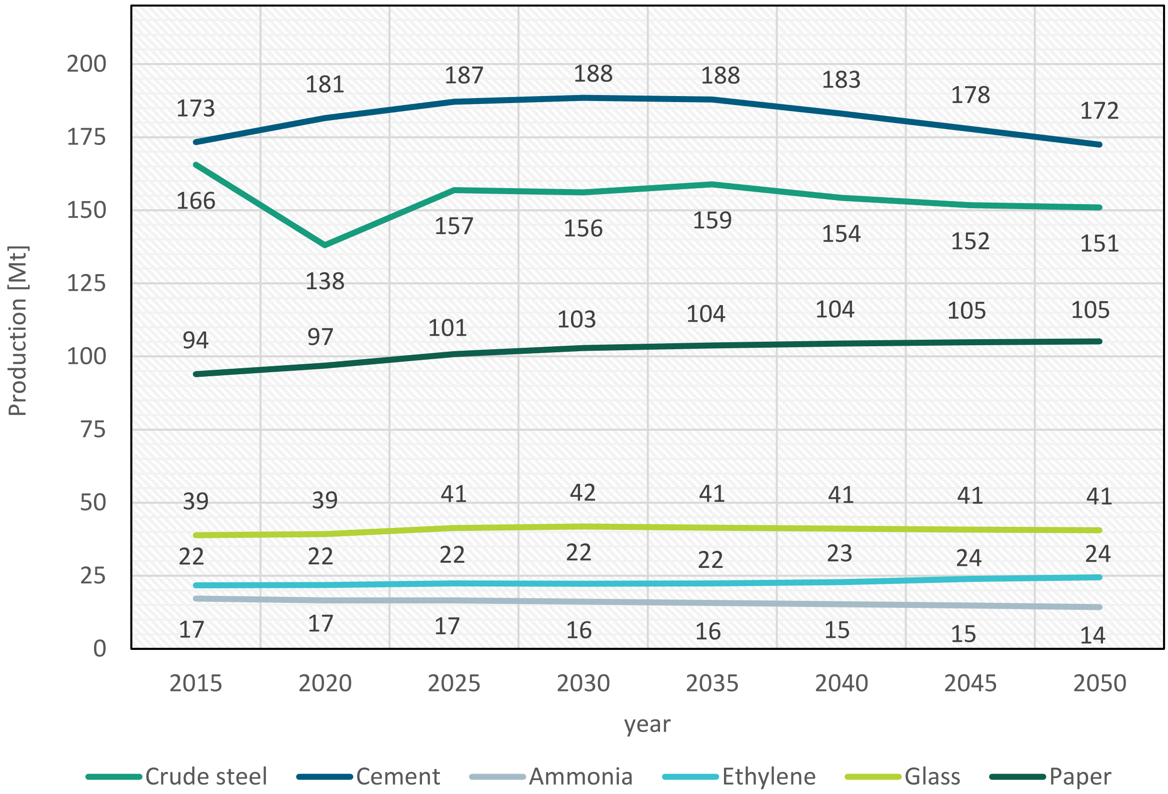

Figure 4: EU 27 + UK assumed production output of selected basic material products in Mt (2015-2050)

Secondary production routes often have lower energy consumption than primary routes, and as such, expanding circular economy practices holds significant potential for decarbonising industry. In addition to reducing GHG emissions, circular economy measures can also contribute to increasing industrial resilience by decreasing the dependencies on raw material imports. Therefore, in this study, we assume a strong expansion of policy support and regulations that result in increasing production via secondary routes, especially in sectors offering high potential. For instance, increasing the share of electric steel production from 42% in 2018 to approximately 60% by 2050 implies a 26 Mt increase in secondary steel production compared to 2018. In the short term, this provides immediate GHG reduction benefits by reducing the coal and coke used in the conventional primary route and, in the long term, leads to a significant reduction in hydrogen demand. In order to ensure a high degree of comparability between scenarios, the assumptions on material efficiency and circular economy are identical in both. Table 3 provides an overview of the main assumptions regarding material efficiency and the circular economy.

Table 3: Overview of the major material efficiency and circular economy assumptions by sub-sector

Product	Material efficiency and demand assumptions	Circular economy assumptions
Steel	More efficient steel use and substitution result in a decrease in production	Increase secondary steel share from 42% (2018) to 60% (+26 Mt) by 2050
Cement and lime	20% decrease in the clinker share, efficient concrete use and substitution results in a decrease in production. Reduced demand for lime from blast furnaces and power plants	No secondary production route is available
Chemicals	Plastics substitution, reduced fertiliser demand and more efficient material use	~20% increase in mechanical recycling compared to today
Glass	13% decrease in container glass due to more efficient use	Increase flat glass recycling
Paper	Structural change: Graphic paper reductions are overcompensated by packaging demands	Recycling share increases in some countries, but a relatively saturated market

3.1.2 Iron and steel industry

The iron and steel industry is an essential sector for the EU27 + UK economy, accounted for 3% of industry GVA in 2015, and provides the backbone for industrial development, infrastructure, and construction. However, the iron and steel industry is also one of the most significant GHG emitters and was responsible for 18%[5] (157 Mt CO_2 equivalent) of the total industrial GHG emissions in 2019 in the EU 27 + UK[6] (EEA greenhouse gases - data viewer). As such, the iron and steel industry is very carbon-intensive and its decarbonisation is essential if the EU is to meet its target of climate neutrality. The EU 27 + UK iron and steel sector is one of the largest in the world, producing more than 168 million tonnes of crude steel in 2018, and the primary production route using blast furnaces accounts for approximately 58% of steel production (worldsteel association 2019). This process uses iron ore as a raw material and relies heavily on coal, coke, and natural gas (NG) as reducing agents and energy carriers. The reduction of iron ore in the blast furnace to produce pig iron is responsible for most of the direct GHG emissions. The secondary production route using electric arc furnaces (EAF) to melt steel scrap has a substantially

[5] Including 1.A.2.a - Iron and Steel and 2.C.1 - Iron and Steel Production.

[6] Based on EUROSTAT definition, coal demand for direct reduction in blast furnaces is excluded.

lower specific energy consumption per tonne of steel produced than the primary route. In addition, electricity is the main energy carrier here.

The assumed transformation strategy for the iron and steel sector recognises that, while increasing the utilisation of steel scrap can contribute to decarbonising existing crude steel production routes, EU steel production cannot rely completely on secondary raw material flows alone. The availability of steel scrap will limit expansion in the time horizon towards 2050. Therefore, we also consider a complete shift in primary steel production from blast furnaces to direct reduced iron (DRI). Table 4 provides an overview of the major assumptions for the iron and steel industry.

For primary steel production, the sponge iron produced from the direct reduction of iron using hydrogen (H2-DRI) will be melted and processed directly into crude steel using EAF. As a result, steel producers have two options, either integrate DRI into the steelmaking process and feed it directly into EAF, or decouple DRI production and steelmaking. Therefore, one possibility discussed is that in the future DRI will be imported as hot briquetted iron (HBI) from regions with significantly favourable conditions such as lower production costs of CO2-neutral hydrogen, availability of iron ore, and industrial infrastructure

Table 4 Overview of the major assumptions for iron and steel by scenario

	H2+ / Elec+	Elec+_VC
Energy efficiency	Ambitious efficiency progress through the use of the best available technology (BAT)	
Material efficiency	9% decrease in crude steel production compared to 2018	
Circular economy	Increase in secondary steel share from 42% (2018) to 60% (+26 Mt) by 2050	
Process switch	H2-DRI (56 Mt by 2050)	A limited shift toward H2-DRI (25 Mt) and 34 Mt import of HBI

In the H2+ and Elec+ scenarios, we assume integrated European production. Therefore, the hydrogen direct reduction (H2-DRI) production capacity is projected to increase to approximately 14 Mt by 2030 and fully replace blast furnace primary steel production by 2050 (see Figure 5). Additionally, the share of secondary steel production is expected to increase from 42% in 2018 to approximately 60% by 2050, a 26 Mt increase in secondary steel production compared to 2018. In the Elec+_VC scenario, we assume a restructuring of the steel production value chain. As a result, the DRI capacity in Europe is expected to reach only 25 Mt by 2050 and imported sponge iron in the form of HBI for EAF will fill the production gap left from phasing out blast furnaces.

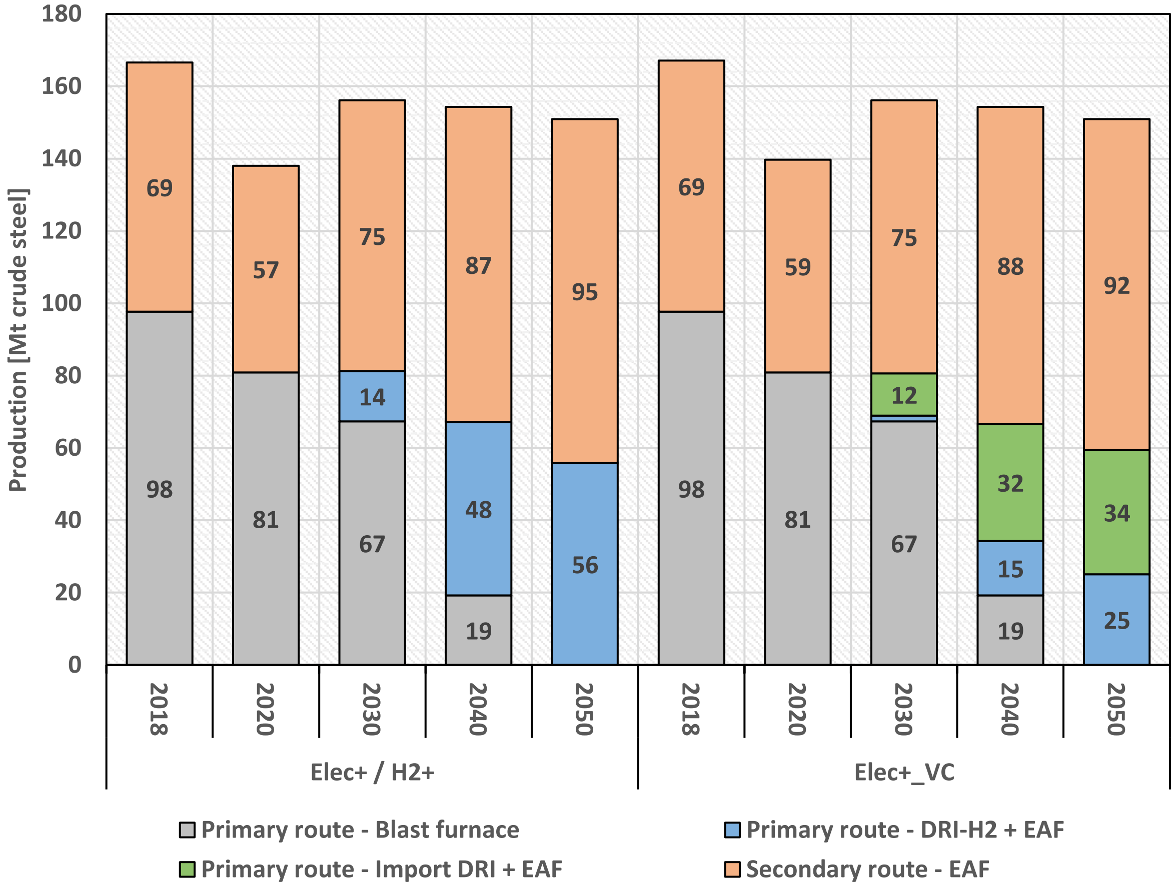

Figure 5 EU 27 + UK crude steel production by production route and scenario (2018-2050)

3.1.3 Chemical industry

The (petro-) chemical industry processes raw materials (feedstocks) such as oil, naphtha and gas to produce a wide range of products, including plastics, fertilisers, pharmaceuticals, and synthetic materials. This sub-sector is essential for the EU economy; in 2015, the EU chemical industry accounted for 15% of industry GVA. However, the sector's energy demand remains heavily reliant on fossil fuels, with an average annual final energy demand of 1678 TWh between 2015 and 2019, including petrochemical feedstocks. Fossil fuels supply 83% of the energy demand in the EU chemical industry, and are both a source of energy and a feedstock for production. This has resulted in the chemical industry contributing 61 Mt CO_2 equivalent (7% of industrial GHG) to industrial GHG emissions in 2019, with ammonia production and petrochemicals the largest contributors (Statistics | Eurostat 2022). Also of huge significance is the CO_2 embedded in chemical products like plastics etc.

Chemicals such as ammonia, methanol, and ethylene serve as feedstocks for various downstream industries. Ethylene (C_2H_4), for instance, is building block for many plastics and synthetic materials, whereas ammonia (NH_3) is used primarily in the production of fertilisers. Currently, the predominant production route for chemicals like ammonia and ethylene relies on fossil fuels as both feedstocks and energy carriers. Ethylene production primarily uses naphtha derived from crude oil, while ammonia production relies heavily on natural gas (CH_4). In the steam cracking process, naphtha is heated to high temperatures in the presence of steam, which breaks down the hydrocarbon molecules into high value chemicals (HVC), such as ethylene. The Haber-Bosch process combines nitrogen from the air with hydrogen from natural gas to produce ammonia. At present, most hydrogen is produced from natural gas via steam reforming.

Table 5 Overview of the major assumptions for the chemical industry by scenario

	H2+/Elec+	Elec+_VC
Energy efficiency	Ambitious efficiency progress through the use of best available technology	
Material efficiency	Plastics substitution, reduced fertiliser demand and more efficient material use	
Circular economy	~20% increase in mechanical recycling compared to today	
Process switch	Ethylene: 80% MTO (20 Mt) 20% ESC (4 MT) Ammonia:100% H_2	Ethylene: Import of green ethylene and limited domestic production via MTO (4Mt) Ammonia:100% of the EU's demand will be imported

The assumed transformation strategy to achieve a CO_2-neutral chemical sector involves substituting the use of petrochemical feedstocks with CO_2-neutral alternatives, and adopting a CO_2-neutral heat supply. In the H2+ and Elec+ scenarios, we assume that the conventional steam cracker (CSC) route for ethylene production will be phased out by 2050. As shown in Figure 6, 80% of ethylene production will shift to the Methanol-to-Olefins (MTO) process, which utilises methanol produced from CO_2-neutral hydrogen and captured carbon dioxide to generate HVC such as ethylene and propylene. The remaining HVC production will be based on green naphtha and electrical steam crackers (ESC). In the Elec+_VC scenario, a limited shift towards the MTO route (4 Mt by 2050) is assumed, while imported ethylene will offset the production lost from phased-out plants. The assumptions regarding ammonia production are that, in the H2+ and Elec+ scenario, the Haber-Bosch process will be completely converted to utilise CO_2-neutral hydrogen by 2050 (see Figure 6). In the Elec+_VC scenario, all ammonia production will be relocated outside of the EU by 2050.

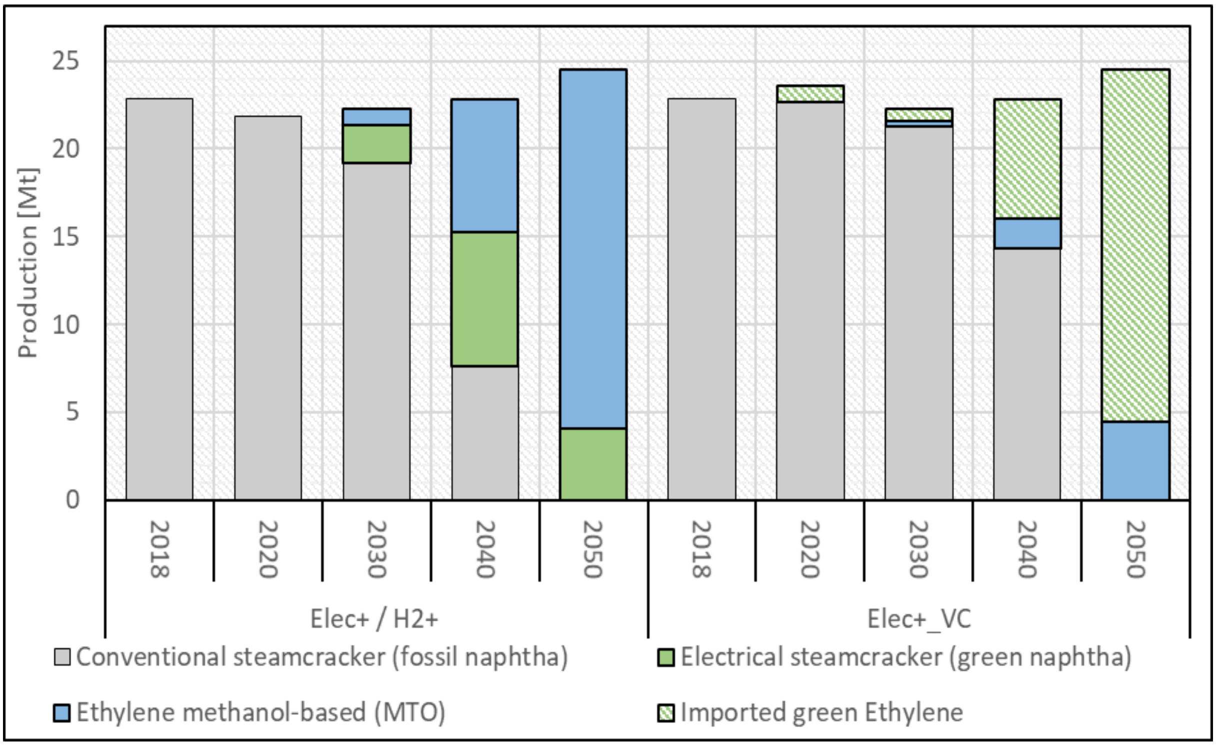

Figure 6: EU 27 + UK assumed ethylene production by production route and scenario (2018-2050)

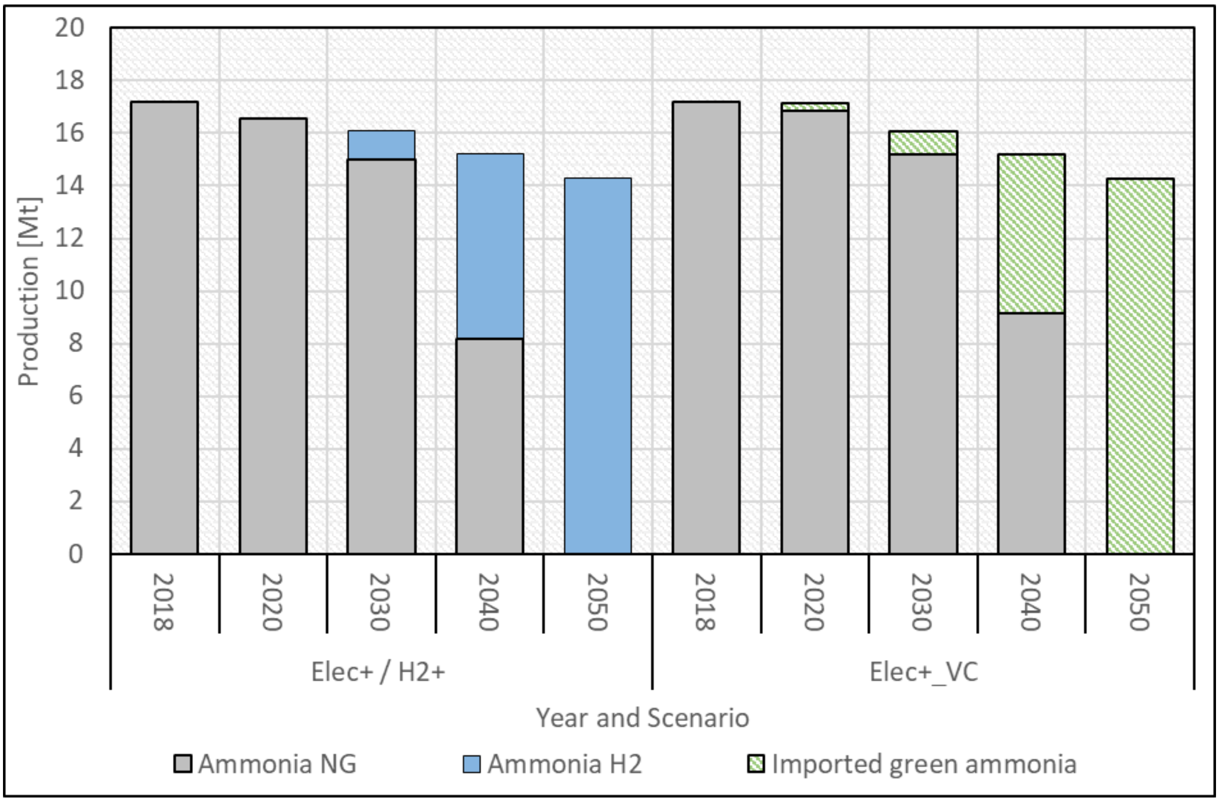

Figure 7: EU 27 + UK ammonia production by production route and scenario (2018-2050) Forecast

3.2 Results

3.2.1 Total energy demand and energy carrier mix

This section shows results of the total industrial energy demand, which consists of final energy demand (FED) as defined by Eurostat plus demand of energy carriers used as raw materials in the chemical industry (feedstocks). In 2018, the total energy demand (TED) for industry in the EU 27 + UK was 4,408 TWh, with the chemical industry accounting for the highest energy demand (39% of TED), followed by the iron and steel industry (14%). The breakdown of this total energy demand into end-uses and sub-sectors in Figure 8 shows that process heating is the largest end-use with about 2000 TWh energy demand in 2018. This breaks down relatively equally into high-temperature process heating in furnaces (>500°C) and low- and medium-temperature process heating for steam and hot water generation. The energy demand for high-temperature process heating is projected to decrease from 1011 TWh in 2018 to about 618 TWh in 2050. This significant decrease is primarily driven by the shift from primary to secondary production routes, which are often substantially more energy-efficient. For instance, energy demand in the iron and steel industry is projected to decrease by 40% by 2050, reaching 250 TWh in 2050 driven by the shift from primary production in blast furnaces to scrap-based secondary steel production and use of direct reduction technology. Feedstock demand for the chemical industry is estimated to 1090 TWh in 2018 and is assumed to increase slightly in the Elec+ scenario. Mechanical energy is the fourth main end-use and accounted for nearly 900 TWh in 2018. It is already fully based on electricity and also includes other smaller end-uses as for example lighting.

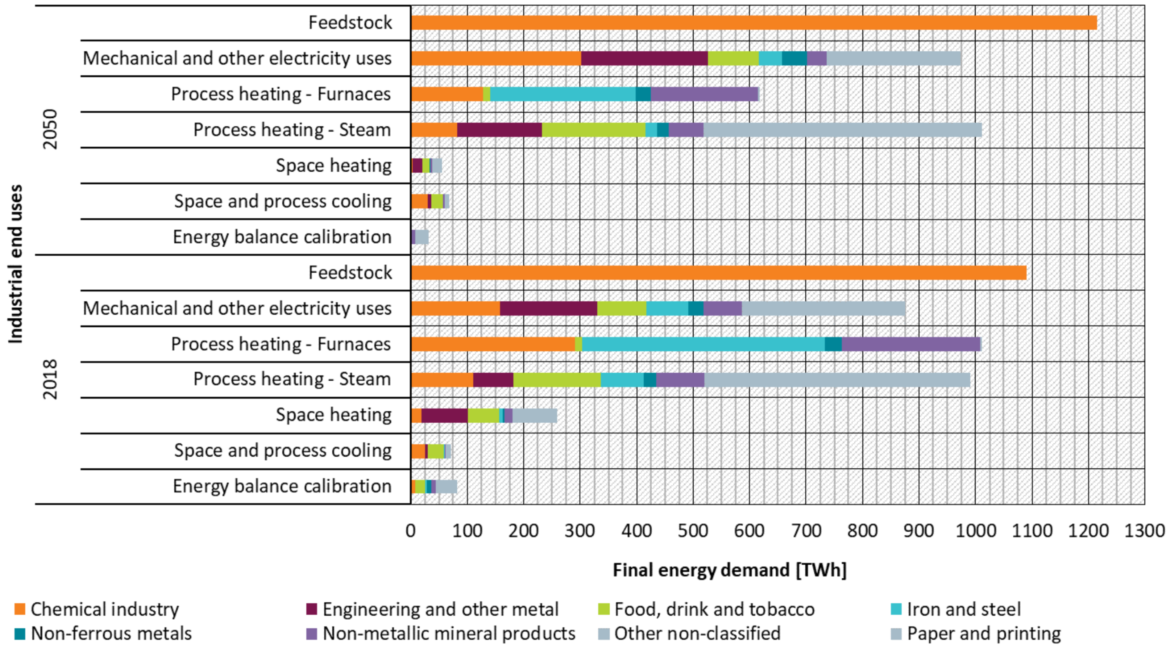

Figure 8: Projected total energy demand in industry in 2018 and 2050 (Elec+ scenario) by end-use (EU27+UK, 2018 and 2050). 2018 is based on Eurostat*, and end-uses balance is based on the method from FORECAST model (Rehfeldt et al. 2018)*

Figure 9 shows the **development of total energy demand by energy carrier** (TED). Across all scenarios, there is a continuous decrease in TED between 2018 and 2050. This decrease is driven by efficiency improvements from introducing state-of-the-art technologies, but is also due to accelerated circularity and improved material efficiency. In the Elec+ scenario, TED decreases by 10% from 4408 TWh in 2018 to 3979 TWh by 2050, while in the H2+ scenario, TED decreases by 8% to 4047 TWh by 2050.

The transition to a low-carbon future requires significant changes in the energy mix. Fossil fuels, which accounted for 68% of TED or 2853 TWh in 2018, are completely phased out by 2050. Electricity and hydrogen dominate energy demand by 2050, with minor contributions from ambient heat, biomass, district heating, solar, and geothermal energy.

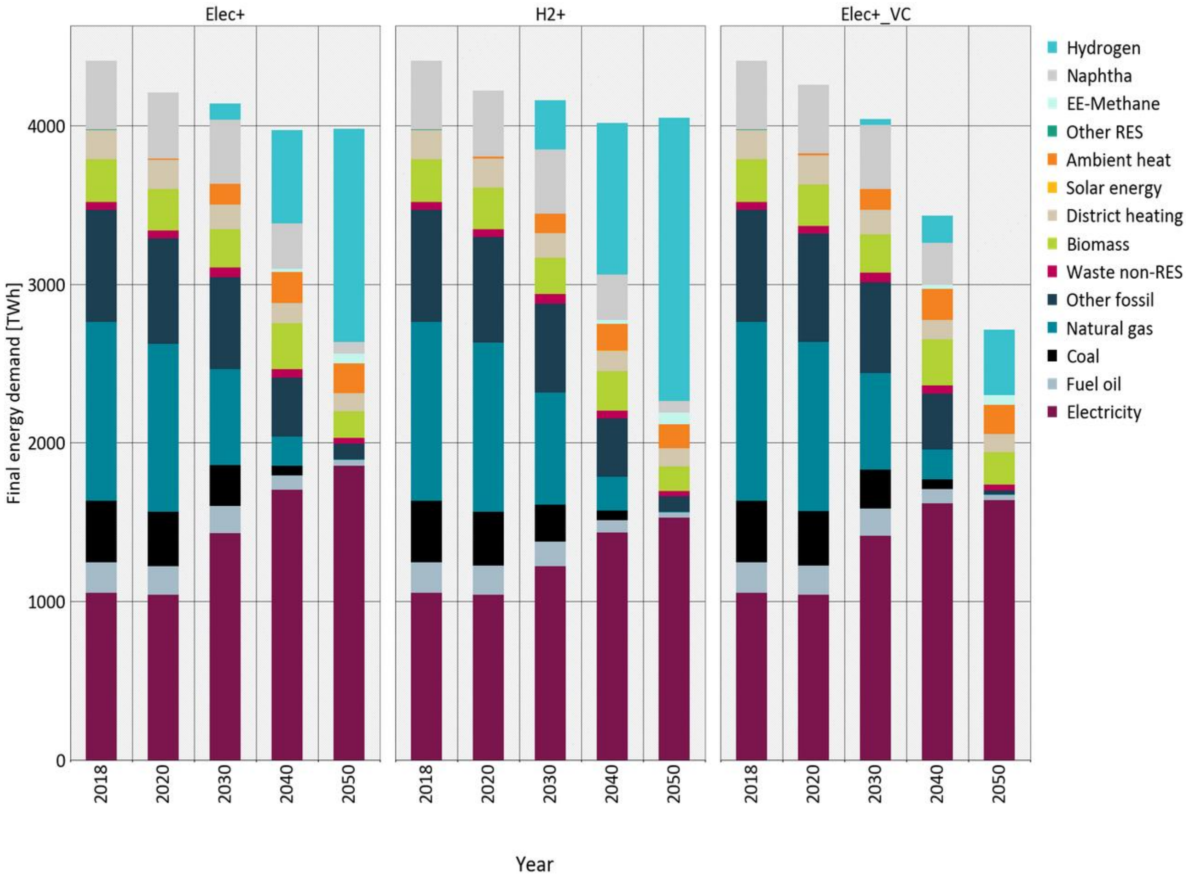

Figure 9: Projected final energy demand plus feedstock demand in industry by scenario and energy carrier (EU27+UK, 2018-2050). 2018 is based on Eurostat and the other years are taken from the FORECAST model

3.2.2 THE ROLES OF HYDROGEN AND ELECTRICITY

Hydrogen is a key pillar of decarbonising European energy-intensive industry, with hydrogen demand estimated to be 1785 TWh in the H2+ scenario, 1343 TWh in the Elec+ scenario and 415 TWh in Elec+_VC sensitivity analysis by 2050. The importance of hydrogen varies in the two main scenarios, but it has an important role in feedstock supply and process heating in both. The transformation of the chemical sector is the primary driver of hydrogen demand in the long-term. The feedstocks for chemical production are currently based entirely on fossil fuels, mainly naphtha and natural gas, and amounted to about 1090 TWh in 2018. Emissions from the conventional production of ammonia, methanol, and ethylene can be avoided by switching to alternative process routes and using green hydrogen. In both main scenarios, it is projected that 1042 TWh of hydrogen will be needed as feedstock in the chemical industry. The hydrogen demand for process heating adds about 310 TWh in the Elec+ and up to 742 TWh in H2+ depending on the take-up of direct electrification (Figure 10). By 2050, approximately 75% of the hydrogen demand for feedstock will be concentrated primarily in northern Europe, with the largest consumers being Germany (218 TWh), France (139 TWh), the Netherlands (139 TWh), Belgium (94 TWh), and the United Kingdom (87 TWh).

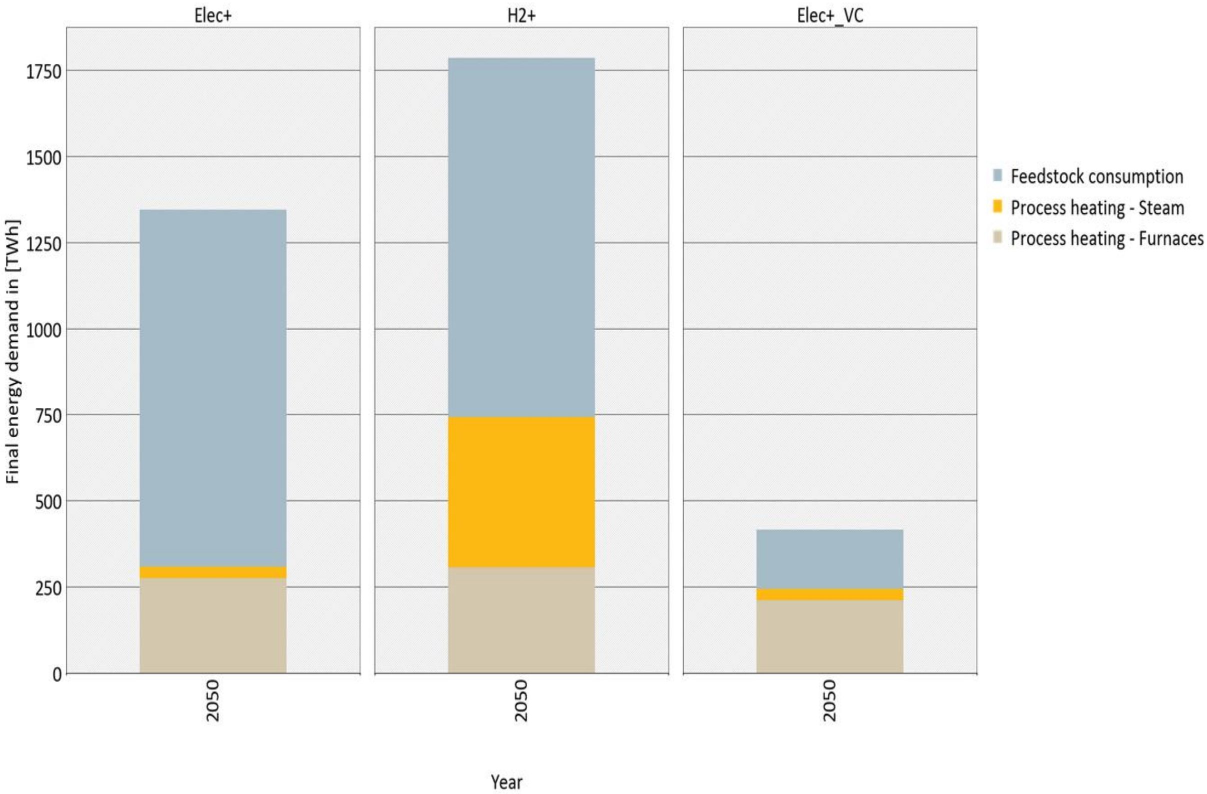

Figure 10: Hydrogen demand in industry by scenario and energy carrier (EU27+UK, 2018-2050)..

The demand for hydrogen as a **feedstock** starts to take off from 2025 with demonstration and pilot projects, leading to 50 TWh of H_2 by 2030. The scaling up is expected to accelerate between 2030 and 2040, with H_2 demand for feedstocks reaching 405 TWh by 2040 (Figure 11). However, it is important to note that the demand for hydrogen as a feedstock is prone to uncertainty. For instance, a limited shift to the MTO route and the restructuring of the value chain through importing hydrogen derivatives such as green ammonia or ethylene could significantly affect hydrogen demand. The Elec+_VC sensitivity scenario reflects the possibility of such changes, leading to a significant decrease in H_2 demand, which results in 95 TWh of H_2 for feedstock by 2050.

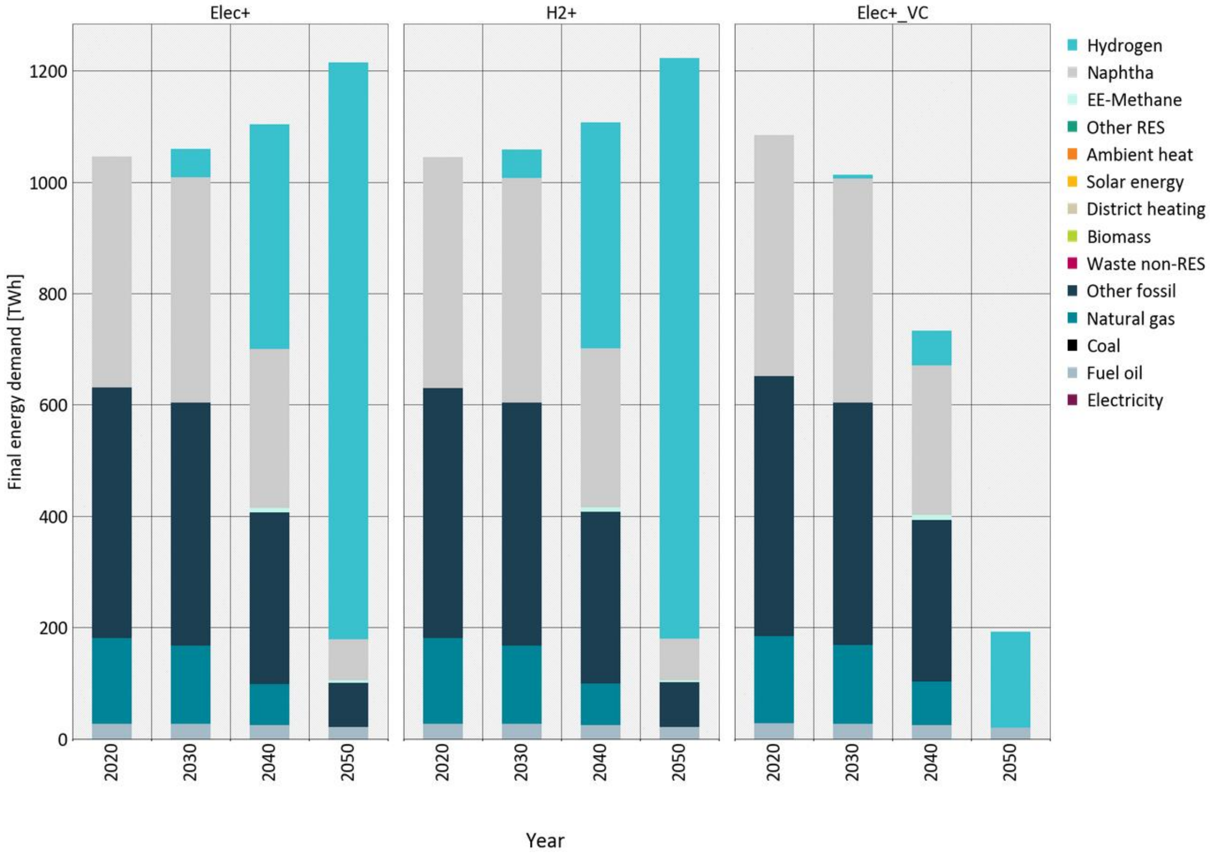

Figure 11: Feedstock demand in the (petro-) chemical industry by scenario and energy carrier (EU27+UK, 2020-2050).

Figure 12 shows the development of direct **electricity consumption** by end use. It is defined as final energy, so excludes indirect uses such as hydrogen production via electrolysis. European electricity demand is projected to continue growing in all scenarios. By 2050, the share of direct electricity in total final demand is expected to reach 47% in the Elec+ scenario and 38% in the H2+ scenario, a significant increase compared to the 24% recorded in 2018.

To comply with the goals of 55% GHG reduction by 2030 and becoming climate neutral by 2050 requires an increase in renewable electricity. In 2018, 70% of electricity demand in industry was used for mechanical energy and lighting as well as processes that are already electrified today, such as the electrolysis of aluminium (6%) or electric scrap-based steel. In the Elec+ scenario, electricity demand increases to about 1855 TWh by 2050 (Figure 12). Electricity plays an increasingly important role towards 2050 in this scenario with the electrification of process heating being the primary driver of the overall increase. Electricity demand in the H2+ scenario increases by 478 TWh compared to 2018, with 81% of this increase due to the electrification of process heat (388 TWh).

In the Elec+ scenario, there is a substantially higher increase in electricity demand between 2020 and 2030, with 48% (or 387 TWh) of this increase-taking place between 2020 and 2030. In contrast, the electricity demand increase in the H2+ scenario in the same period is only half of this amount (180 TWh). However, the H2+ scenario requires in turn a much higher quantity of CO2-neutral hydrogen (see above). If this will be generated in Europe via electrolysis, total electricity demand will even be higher in the H2+ than in the Elec+ scenario.

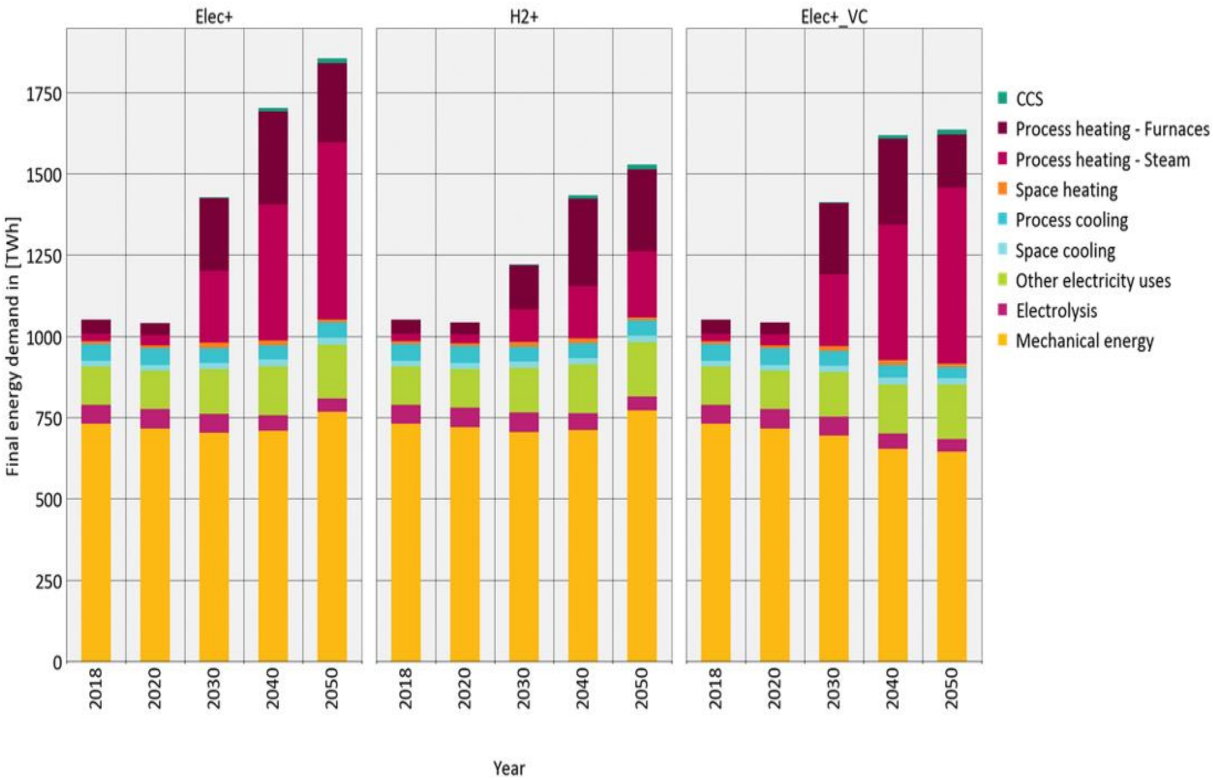

Figure 12: Electricity demand by scenario and end-use (EU27+UK, 2018-2050) defined as final energy (e.g. electricity demand for electrolysers is not included) 2018 is based on Eurostat, subsequent years are the result of modelling

3.2.3 Decarbonisation of Process heating

As process heat represents a significant end-use in industry, particularly in terms of fossil fuel use and CO_2 emissions (see also Figure 8), this section takes a closer look at its changes in the energy mix. Industry uses a wide range of heat temperatures starting below 100°C, e.g. for space heating and process heating using hot water, e.g. in the food industry. Operating temperatures between 100°C and 300 °C used for steam generation can typically be found in the chemical, paper and food industries. Industrial furnaces, e.g. in steel and cement industries, use temperatures mostly above 1000 °C. The challenges associated with the energy mix and technologies to decarbonise process heating differ substantially across applications. The two most relevant groups of applications are steam generation in boilers and combined heat and power (CHP) on the one hand, and high-temperature process heat in furnaces on the other hand. Both are discussed here in more detail beginning with the energy supply of industrial furnaces.

High-temperature process heat is found in different types of **industrial furnaces and kilns**, each tailored to the specific requirements of the industry and site. The iron and steel industry accounts for 42% (equivalent to 429 TWh) of the overall demand for high-temperature process heat followed by the chemical and non-metallic sectors, with 29% and 24%, respectively. The electrification of high-temperature processes depends on the sector and process, with some industries benefitting from mature electrification technologies, while others face significant technical and economic barriers. Consequently, hydrogen has emerged as a pivotal element for decarbonising high-temperature process heat, and plays a substantially greater role here than in steam generation.

High-temperature processes rely heavily on hydrocarbons, with around 91% (920 TWh) of the energy required in 2018 from fossil fuels (Figure 13). In 2018, the prevalent energy carriers for industrial high-temperature furnaces were gas and coal, accounting for 38% (386 TWh) and 29% (298 TWh) of energy demand, respectively. In both scenarios, fossil fuels start to decrease by 2030 and are almost phased out completely by 2050. In the H2+ scenario, hydrogen plays an important role for high-temperature heat process by 2030 with 128 TWh. Hydrogen becomes the dominant energy carrier for industrial furnaces by 2050, with about 305 TWh in the H2+ scenario and 275 TWh in the Elec+ scenario. In Elec+, hydrogen demand is driven by the transition in the steel industry (145 TWh), but also by the technical requirements of furnaces and processes for the non-metallic industry.

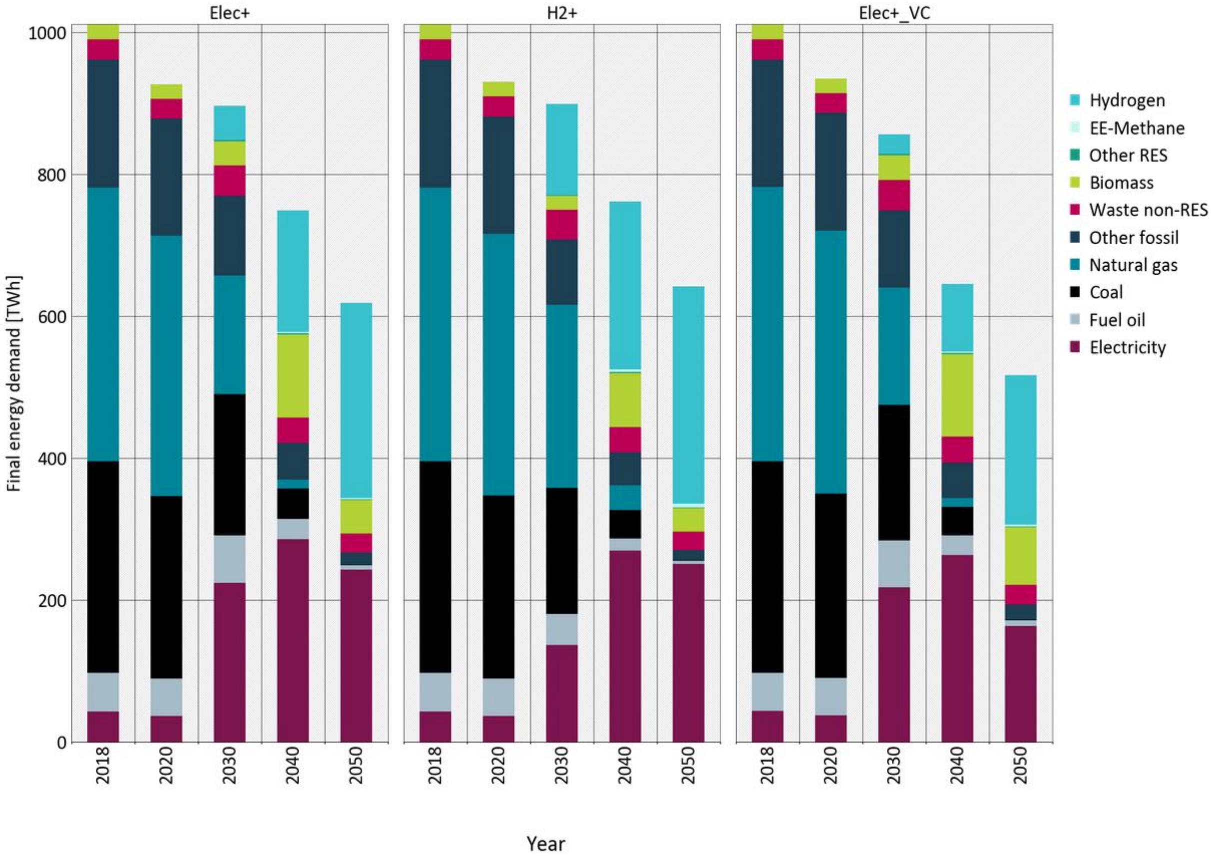

Figure 13: Development of final energy demand high-temperature process heat in industrial furnaces by scenario and energy carrier (EU27+UK, 2018-2050) 2018 is based on Eurostat and the other figures are the result of modelling.

The supply of **low- and medium-temperature process heat** (steam and hot water) accounted for about 42% (990 TWh) of final energy demand in 2018 as shown in Figure 16. In 2018, the main energy sources for steam and hot water generation were natural gas 34% (338 TWh) and biomass 26% (252 TWh). The two main scenarios illustrate different developments. In the Elec+ scenario, electricity becomes the most significant energy carrier accounting for more than 54% (546 TWh) of low- and medium-temperature process heat supply and its demand is projected to increase rapidly in this scenario from 24 TWh in 2018 to 221 TWh by 2030. The increased utilisation of electricity is supported by the fact that technologies are ready and commercially available for this temperature level (electric boilers and industrial heat pumps) and that a certain share of lower temperature heat can be efficiently supplied by industrial-sized heat pumps, indicated by the role of ambient heat in the FED. In contrast, the H2+ scenario shows a modest increase in electricity demand to 100 TWh and 205 TWh by 2030 and

2050, respectively. However, this is compensated by the higher hydrogen demand in this scenario of 130 TWh and 436 TWh by 2030 and 2050, respectively.

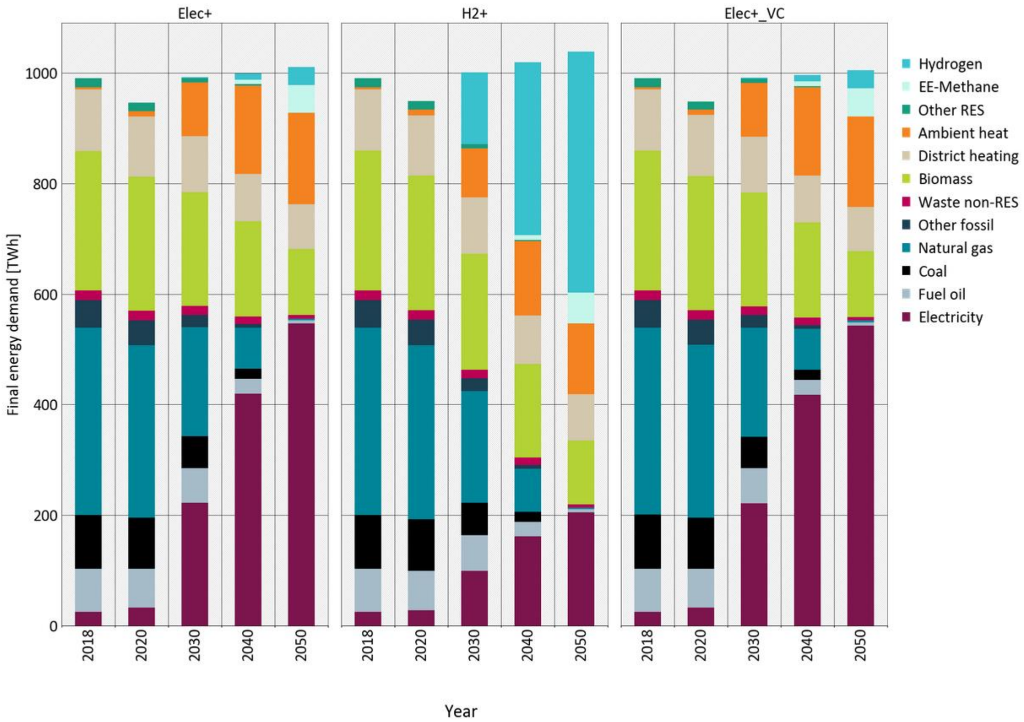

Figure 14: Development of FED for low and medium-temperature process heat as steam and hot water by scenario and energy carrier (EU27+UK, 2018-2050). 2018 is based on Eurostat and the other figures are modelling results

4 ENERGY SYSTEM ANALYSIS

4.1 ASSUMPTIONS AND METIS PARAMETRISATION

4.1.1 SYSTEM BOUNDARY AND SCOPE

The energy system analysis uses the optimisation model METIS. It is a detailed energy system optimisation model covering the EU27, the United Kingdom (UK), Norway (NO), Switzerland (CH), Bosnia and Herzegovina (BA), Montenegro (ME), North Macedonia (MK), and Serbia (RS). The model uses a single node to represent each country and includes a wide range of energy supply, storage, cross-border transmission capacities and demand technologies, which are referred to as assets. This is an advanced energy system model applying an integrated optimisation approach to the capacity and dispatch of different power generation technologies. METIS optimises the capacity expansion and dispatch of electricity, gas and hydrogen generation, transmission, storage and demand assets, while also considering the demand for hydrogen derivatives such as ammonia, synthetic gas, and liquid fuels, which is converted into hydrogen demand. METIS determines the optimal portfolio of technologies and their hourly utilisation across an entire year. One exception is nuclear power, which has exogenous capacity expansion, but endogenous dispatch. The primary objective of the optimisation process is to minimise the total system costs, which include not only generation costs but also the penalty costs associated with unserved load. Unserved load refers to electricity demand that cannot be met due to insufficient generation capacity. Within the model, generation technologies are subject to capacity and dispatch optimisation. The objective of this modelling exercise is to optimise the energy system of the target year 2050.

4.1.2 ENERGY DEMAND

In METIS the total energy demand (TED) is exogenous input. The FORECAST model provides the demand for industry and the demand from other sectors is taken from the EU's MIX-H2 scenario (EUROPEAN COMMISSION 7/14/2021).

Figure 15 provides a breakdown of TED by energy carrier and scenario in the year 2050, as well as a comparison with the final energy and feedstock demand of the EU in 2019 (excluding ambient heat).[7]

Figure 15 indicates a 24% reduction in TED by 2050 compared to 2019 in both scenarios. This is mainly driven by efficiency gains in the building sector and the diffusion of energy-efficient electric vehicles in transport. Fossil fuels are completely phased out by 2050; these are substituted by electricity and hydrogen, which are the main energy carriers in 2050 in both scenarios. Hydrogen plays a stronger role in the H2+ scenario, as it is more widely used for industrial process heat, resulting in an additional hydrogen demand of 450 TWh compared to the Elec+ scenario. In the Elec+ scenario, the electrification of process heat plays a bigger role, resulting in an additional electricity demand of 320 TWh compared to the H2+ scenario. More detailed discussion of the respective assumptions in both scenarios is found in section 3.

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[7] Figure 15 does not show ambient heat, which has no impact on the energy system as a non-commercial energy carrier. When we include the role of ambient heat, the potential decrease in TED in Elec+ increases by additional 37 TWh by 2050 when compared with the H2+ scenario.

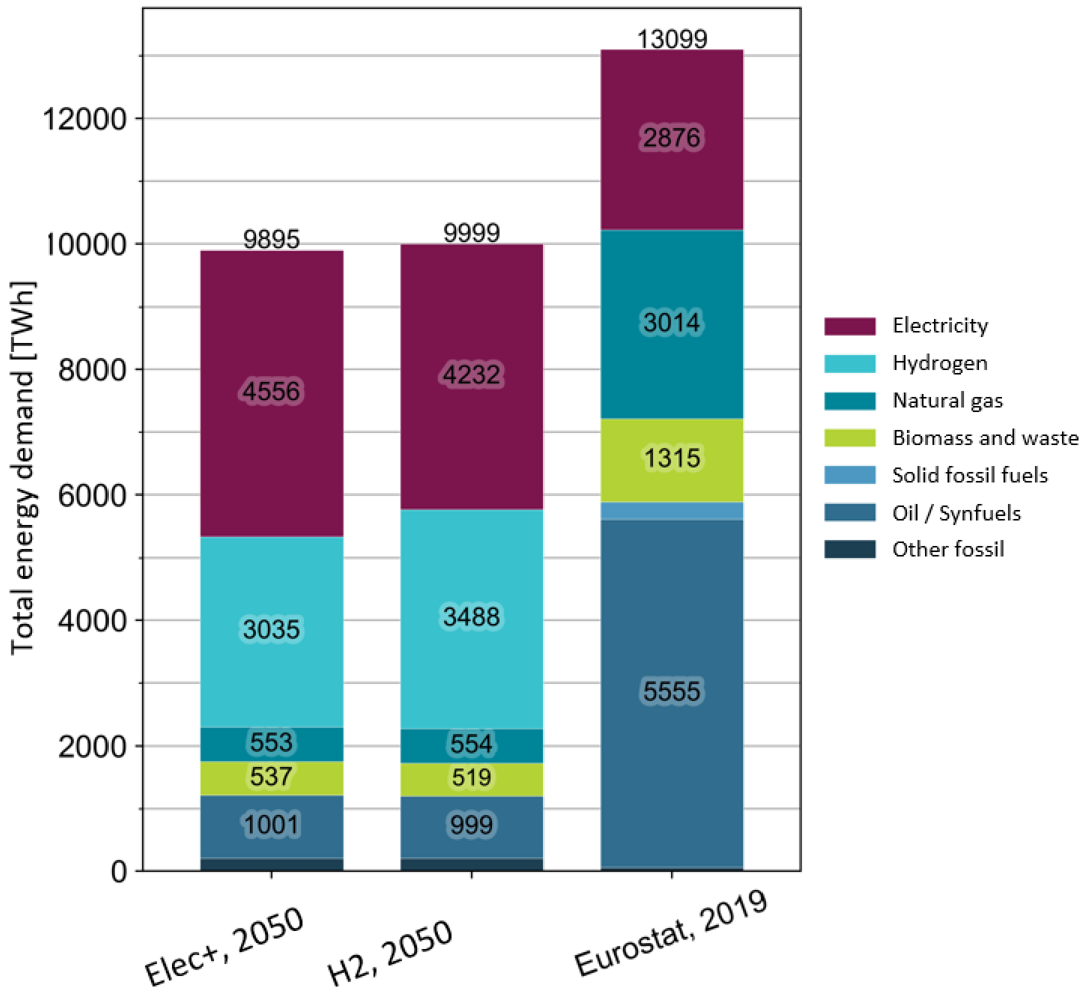

Figure 15: Total energy demand (including feedstocks, excluding ambient heat) in 2050 by scenario and energy carrier for the EU27+ UK, NO, CH, BA, ME, MK, RS (Elec+ and H2+ are shown for the year 2050 and assume that all remaining hydrocarbons are based on synthetic climate-neutral fuels)

4.1.3 COST POTENTIAL CURVES FOR RENEWABLE ENERGY

The deployment of renewable energy sources in METIS follows a multi-dimensional approach that takes into account both cost and generation profiles while ensuring an hourly demand equilibrium for all modelled energy carriers. This approach seeks to optimise the energy mix by deploying the most cost-effective technology while ensuring that the energy generated matches the hourly demand. The cost-potential curves for renewable generation provide valuable information about renewable energy source potentials clustered by costs, taking into account the location-specific variation in load factors across a country. As shown in Figure 16, from a technical perspective, nearly 10,000 TWh of renewables with costs of less than 50 EUR/MWh have been identified. The economic potentials below 40 or even 30 EUR/MWh mainly consist of solar PV and onshore wind power. Offshore wind potentials become relevant at generation costs above 40 EUR/MWh (fixed-bottom turbines) or 50 EUR/MWh (floating turbines), while concentrated solar power (CSP) potentials are the most expensive, starting above 90 EUR/MWh. The cost-potential curves are based on previous work packages. For further information about the assumptions and methodology, refer to (Artelys 2023).

The cost-potential curves for renewable generation enable a more detailed and realistic representation of renewable energy source deployment. The factor of land use is an essential parameter when determining the land available for renewables, as it considers the technical feasibility and environmental impact of different types of land use. In the context of forested land, for example, it is assumed that PV and CSP technologies are not technically feasible. However, wind turbines could be installed on such terrain; a factor of 15% is assumed here. For grassland and shrubland, we assumed a factor of 2% for PV technologies, a decision based on the general desire to minimise further ecological impacts on these areas. The highest land-use factors are assumed for barren land, a terrain that do not offer other economically competitive uses. Even in such instances, factors are capped at 48% of the total barren land area in order to maintain an ecological balance. Finally, for agricultural land, or cropland, we assumed a lower factor for PV technologies, taking into account the potential for Agrivoltaic use. Higher factors are assumed for wind turbines, as the interspace between turbines can accommodate multiple uses.

However, cost-potential curves are context-dependent, i.e. the realization of these technical potentials are dependent on and subject to numerous limitations that must be taken into account when interpreting the model results. Indeed, the techno-economic potentials of renewable energy sources still face major barriers to deployment, such as opposition by local communities, inhibitive local policies and regulatory frameworks, bureaucracy, and the shortage of skilled labour and materials etc. These factors can significantly influence the feasibility of implementing certain technologies.

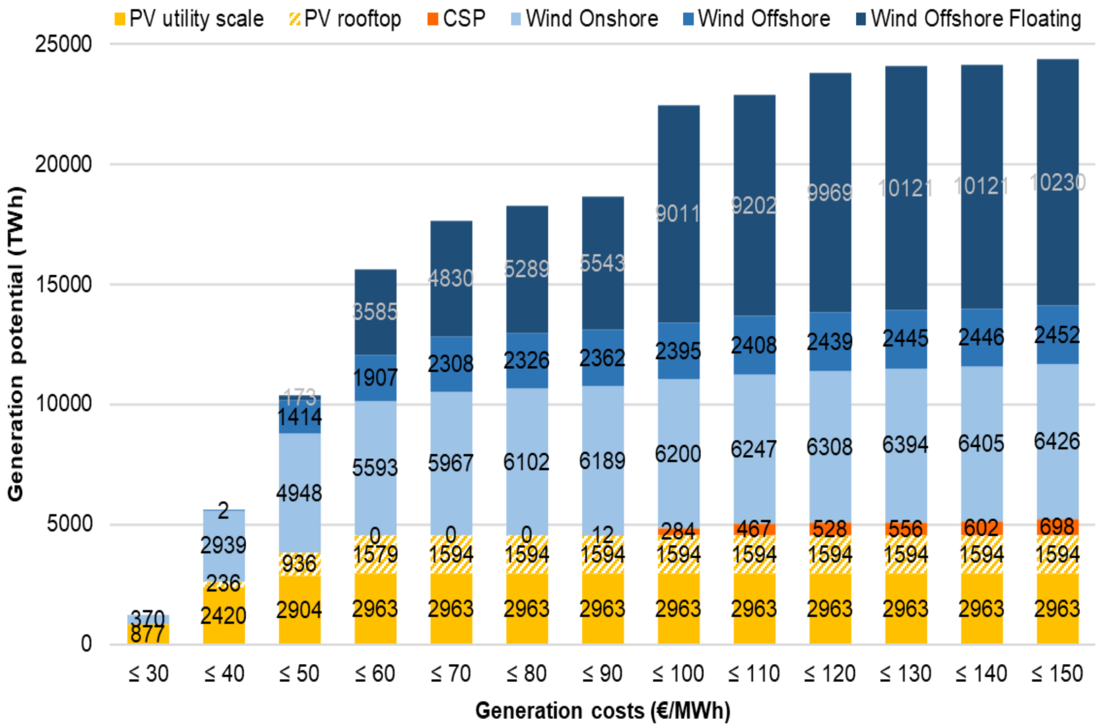

Figure 16: RES-E cost-potential curve for all modelled NUTS1 regions for the weather year 2012 and techno-economic assumptions for the year 2050 (Artelys 2023)

4.1.4 Hydrogen system

The assumptions made about the hydrogen system are particularly relevant in this study, because CO_2-neutral hydrogen will be an enabler for the industry transition. In 2050, the analysis assumes hydrogen could be produced via electrolysis or imported. The flexible operation of electrolysers is modelled to allow them to respond to market conditions, such as low power prices and changes in demand, which can significantly affect the optimal deployment of hydrogen in the energy system. It is assumed that the efficiency of electrolysers is 72%. The investment cost of hydrogen production via electrolysis is 31,300 EUR/MW, including the total annual costs for capital expenditure (CAPEX) and fixed operational expenditure (OPEX) and energy costs over the assumed lifetime of 20 years.

Hydrogen infrastructure is modelled including hydrogen storages and cross-border capacities. New hydrogen pipelines can be built up to a maximum capacity of 100 GW per interconnection between countries at a cost of 3,200 EUR/MW/year[8], or existing gas

[8] This is based on the assumption that the average cost of overland pipelines is 328.27 EUR (fixed operation cost/year) plus 1,295.02 EUR (CAPEX/year) per pipeline direction. Since the pipelines run in both directions (e.g. DE-BE and BE-DE), the total costs double resulting in 3,246.58 EUR/MW/year, which is rounded to 3,200 EUR/MW/year.

pipelines can be repurposed at 25% of the costs, although it is assumed that repurposed pipelines lose 40% of their capacity due to the lower volumetric energy density of hydrogen. We assumed that hydrogen subsea pipelines have higher costs, which are connection-specific. The upper limit of repurposing is based on the existing cross-border gas capacities from the TYNDP 2020 (Ten-Year Network Development Plan) (ENTSO-G). For power transmission investments, costs were derived from the ENTSO-E report and are country-specific, ranging from 20,000 – 30,000 EUR/MW/year, which are notably higher than those for hydrogen infrastructure (ENTSO-E). Hydrogen imports are available, e.g. from MENA via pipeline and have the assumed costs shown in Figure 17. Accordingly, there is a large potential of more than 2000 TWh of hydrogen available at 65 EUR/MWh.

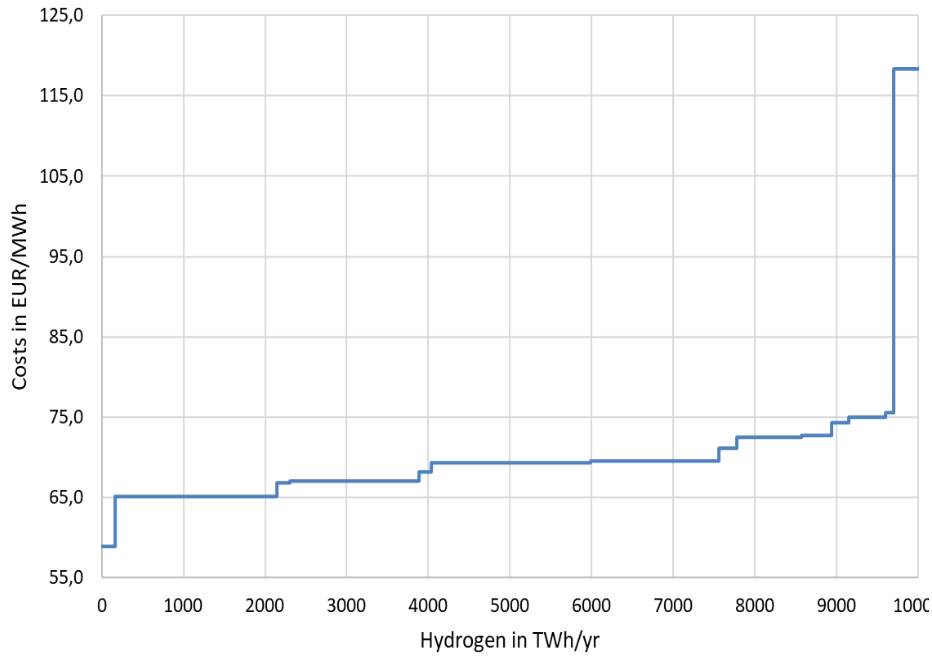

Figure 17: Assumed hydrogen import cost-potential curve for imports from MENA (Lux et al. 2021)

4.2 Results

4.2.1 *Electricity system*

The modelling results demonstrate a significant increase in electricity generation across all scenarios in comparison to 2019. The H2+ scenario projects an electricity generation of 9,409 TWh by the year 2050, while Elec+ is slightly lower at approximately 9,094 TWh by 2050 (see Figure 18). The 400 TWh difference is primarily due to the lower efficiency in the hydrogen energy conversion chain, which includes several steps such as production, storage, transportation, and utilisation, each with their own inherent energy losses. This means that a higher primary energy input is required to achieve the same amount of final energy output compared to electricity. This increased demand is predominantly met by onshore wind energy, which supplies an additional 200 TWh.

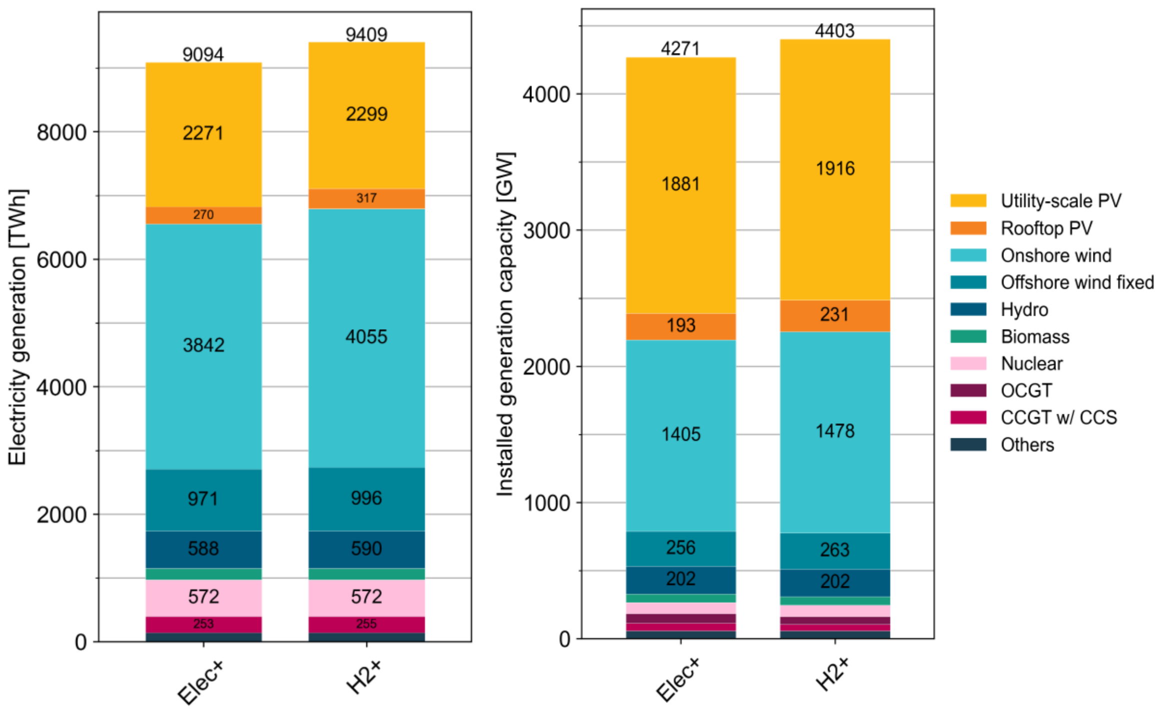

Figure 18: Development of the European energy supply in 2050 by technology in the different scenarios

Both scenarios feature renewable energy sources (RES) as the primary component of their energy systems, with approximately 90% of overall power production. The intermittent sources wind and solar energy contribute up to around 80% of total RES production. Controllable energy sources such as biomass, combined-cycle gas turbines with carbon capture and storage (CCGR CCS), and nuclear all fall below 5% in terms of production; yet remain relevant for supplying the residual load. Although these technologies are not the primary source of electricity production in both scenarios, they will still play an important role in ensuring a stable and consistent energy supply, particularly during times when renewable energy sources like wind and solar energy may not be able to meet demand due to their fluctuating nature.

A closer examination of the generation mix and installed electricity generation capacity (GW) reveals interconnected patterns in both scenarios. Onshore wind energy is responsible for nearly 45% of total production and 32% of the installed capacity, corresponding to 77% and 81% of the available potential under 50 EUR/MWh utilised in the Elec+ and H2+ scenarios, respectively. At a regional level, we observe that France, Benelux, Denmark, Norway, the UK and Ireland deploy almost their entire technical potential for onshore wind power. Utility-scale PV is the most widely installed technology with about 44% of installed capacity, corresponding to 24% of the production. Interestingly, with the exception of Ireland and Scandinavia, utility-scale PV potential is almost fully utilised across European countries (Figure 19). On the other hand, rooftop PV systems are hardly used, with the exception of some Mediterranean countries. The total installed capacity of RES in the H2+ scenario is 132 GW higher than in the Elec+ scenario. This total is made up of 48% onshore wind, 24% rooftop PV, and 23% utility-scale PV.

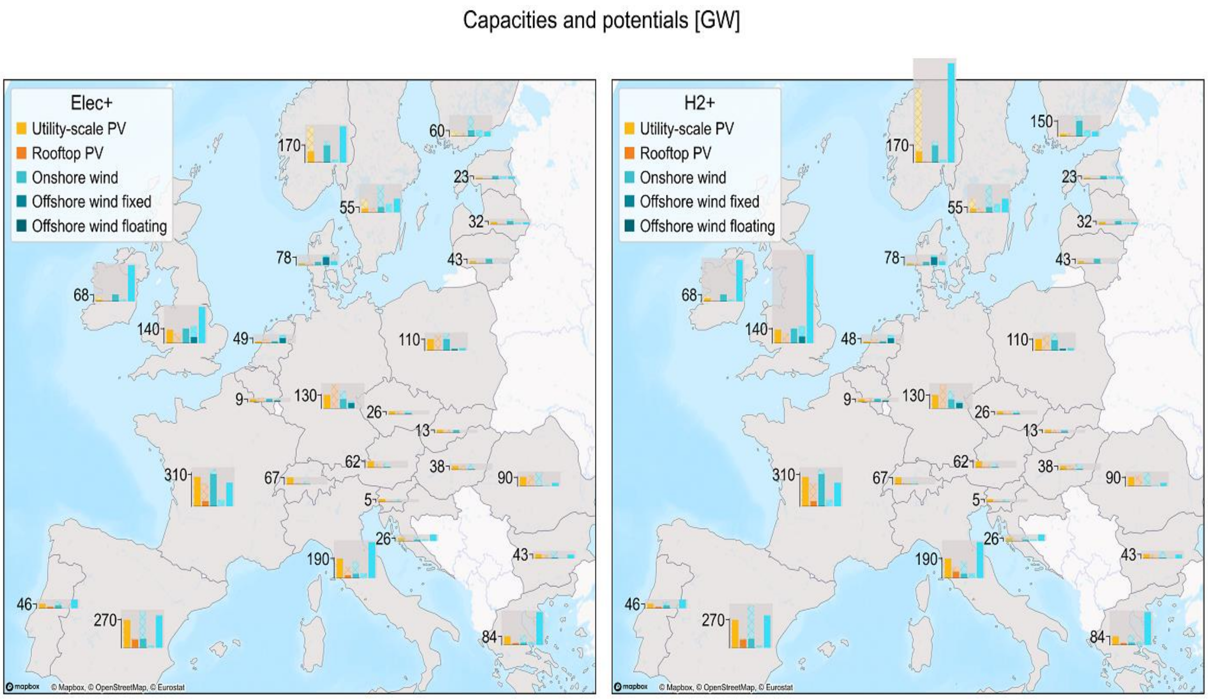

Figure 19 Deployed wind and PV capacities and potentials [GW]. Hatched bars show each country's technical potential for the respective RES technologies (Artelys 2023)

The analysis reveals that the utilisation of renewable energy potential varies significantly across regions and technologies. Prioritizing cost-effectiveness and ensuring efficient utilisation results in 70% utilisation of the utility-scale PV potential. As seen in Figure 19, most European countries have almost fully exploited their utility-scale photovoltaic potentials with the exception of the Nordic countries. North Sea countries exploit their potential for wind energy generation by installing 1000 GW of wind capacity. An interesting observation is the limited use of rooftop photovoltaics, primarily in Southern Europe and Greece. This can be attributed to the assumed absence of subsidies in the modelling in combination with a cost-minimisation approach, which strongly influences the adoption of this technology.

Increased deployment of renewable energy sources implies a need for grid reinforcement. The full potential capacity as defined by the TYNDP is utilised for most connectors, highlighting the importance of robust interconnectivity and the extensive expansion required to accommodate the increasingly regionally distributed demand and supply of renewable energy. For instance, we can observe a significant increase in cross-border exchange capacity between Spain and France. France and Italy, in particular, utilise the maximum capacity permitted by the model. In most cases, the capacities of energy transit routes are fully utilised, highlighting the challenges associated with integrating increased amounts of renewable power into the grid.

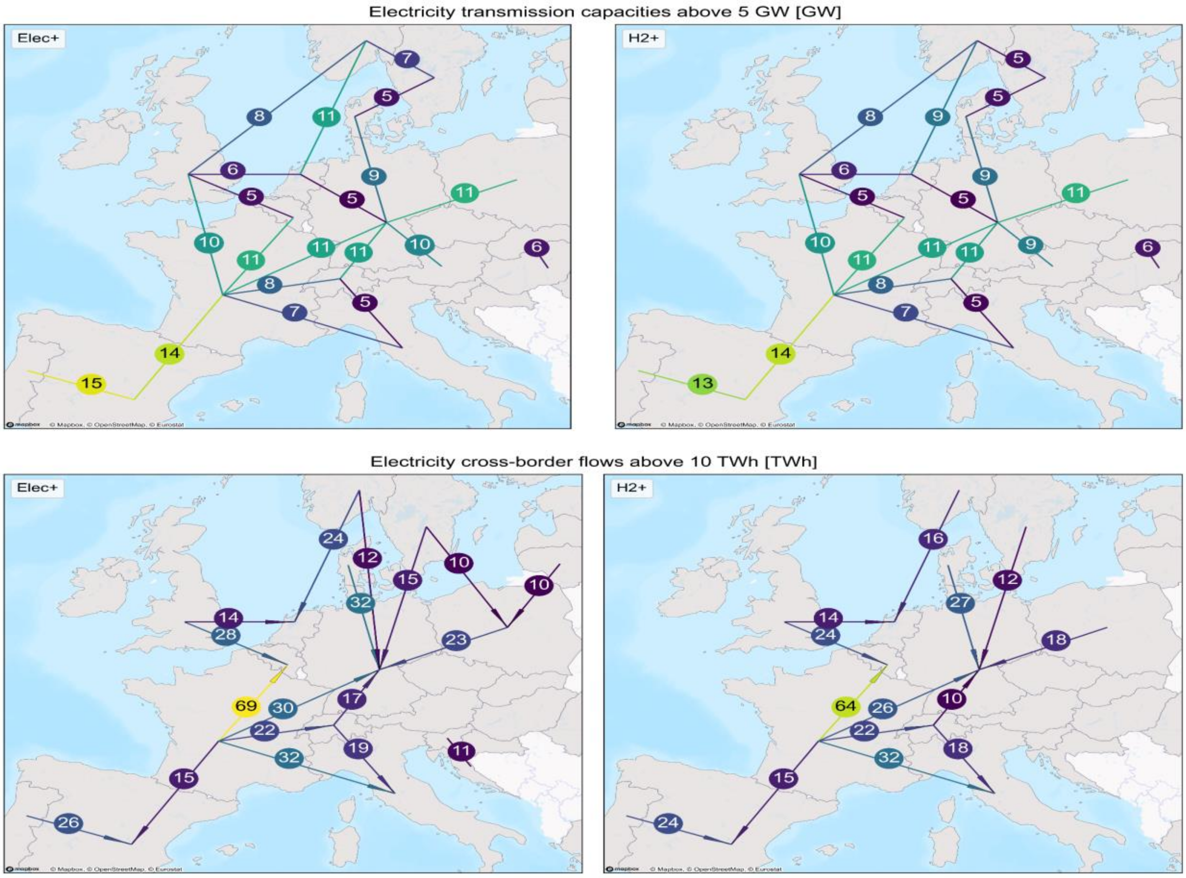

Figure 20: Electricity cross-border flows in the scenarios Elec+ and H2+ [TWh]

Figure 20 shows the annual net cross-border electricity transfers and reveals interesting patterns in both the Elec+ and H2 scenarios: In Elec+, France emerges as Europe's largest producer of surplus electricity, exporting a total of 170 TWh to all its neighbours, with 69 TWh alone going to Belgium as the primary recipient. This highlights France's potential to support neighbouring countries - if it deploys its huge cost-effective RES potentials. In contrast, Germany becomes Europe's largest electricity importer, with 130 TWh of imports, driven by significant demand from heavy industry. Belgium, with 88 TWh of imports, ranks second in terms of electricity imports, highlighting the country's reliance on cross-border electricity transfers to meet its energy needs. These dynamics emphasise the importance of a robust and interconnected grid infrastructure across Europe.

While hydrogen may seem like a promising solution to alleviate the pressure on electrical grids, interestingly, comparing the two scenarios reveals that the increased hydrogen demand in the H2+ scenario does not necessarily equate to a reduced need for electricity grid reinforcement. Instead, technical limits are the primary factor limiting the deployment of grid reinforcement is technical boundaries. RES curtailment levels in both scenarios are similar (around 1% of produced energy), suggesting that increasing the use of hydrogen alone does not significantly alleviate the challenges associated with integrating renewable energy sources into the grid. However, it is important to note that the increased use of hydrogen in industries coupled with a decrease in overall electricity demand does result in reduced cross-border electricity flows, as hydrogen can be used to store and transport energy more locally. This highlights the complex relationship between hydrogen deployment and the need for grid reinforcement.

4.2.2 HYDROGEN SYSTEM

The demand for hydrogen increases to about 3000 TWh in the Elec+ scenario and to about 3400 TWh in the H2+ scenario by 2050, making hydrogen the second most important energy carrier after electricity. In the cost-optimal energy system, the entire demand for hydrogen is covered by domestic production in Europe, with a total of 810 GW and 915 GW of electrolysis capacity installed in the Elec+ and H2+ scenarios, respectively. The marginal costs of the domestic production of hydrogen in this cost-optimal system are about 10% below the assumed lowest import potential of 65 EUR/MWh H_2 (see section 4.2.2). With less optimal deployment of RES and electrolysers, some hydrogen imports via pipeline could become part of the cost-optimal solution (see 4.2.4).

A closer look at the regional distribution of installed capacities reveals the role of individual countries in the future hydrogen system. Figure 21 shows the regional distribution of installed electrolyser capacities and, reveals that central European countries including

Germany, Belgium, the Netherlands and others have minimal or no hydrogen production via electrolysis, despite their substantial demand for hydrogen. This observation can be better understood by considering the cost-optimal approach pursued in the model. Given the lower cost of hydrogen transportation compared to local production and the geographic proximity of these countries to others with more favourable hydrogen production conditions, they benefit more from importing hydrogen at a lower cost than producing it locally. As a result, France (130 GW), Spain (120 GW), the United Kingdom (70GW), and Norway (70GW) install significant electrolysis capacities, generating higher electricity demand for electrolysis than for conventional applications.

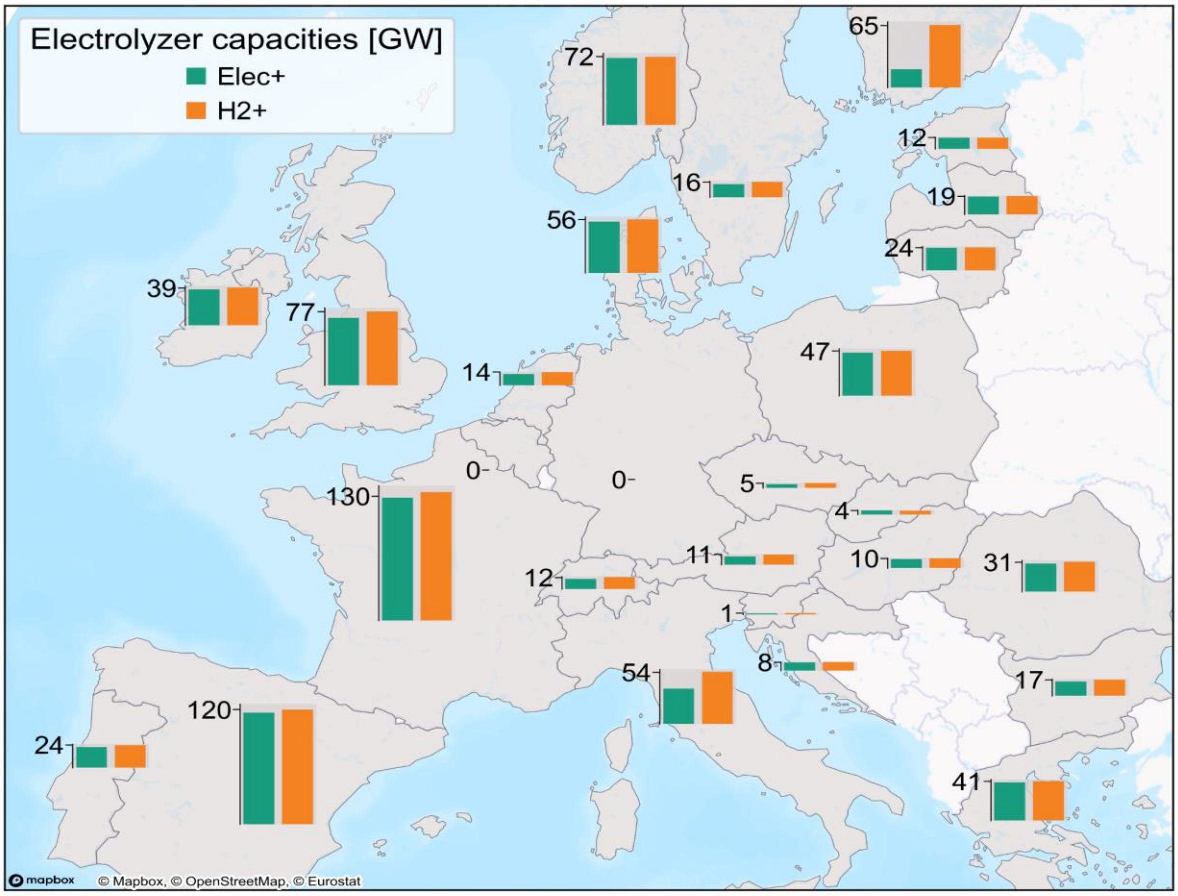

Figure 21: Regional distribution of installed electrolyser capacities in 2050 [GW]

Both scenarios display a similar installed capacity, with the exception of Finland, which adds 50 GW in the H2+ scenario and becomes a major hydrogen exporter. The model results show that, from a cost-optimal perspective, it is preferable to produce hydrogen in countries with high renewable potentials and deploy the necessary hydrogen transport infrastructure.

It has to be emphasised that these are the results of a cost-optimisation approach that considers only a few restrictions and is by no means intended to be a blueprint for implementation. However, it does send the clear message that cooperation among countries is beneficial from the perspective of system costs.

Figure 22 shows the optimised pan-European hydrogen network topology that connects the high-demand centres in Benelux, Germany, and Italy with regions that possess large, low-cost potentials for renewable energy generation. Notable transport corridors include the Baltics, Scandinavia, UK, and the Iberian Peninsula. Also in the Elec+ scenario, there is a substantial demand for a pan-European hydrogen transport network, highlighting its significance for meeting Europe's energy demands in a cost-effective way. In the H2+ scenario, the additional hydrogen demand compared to the Elec+ scenario is primarily supplied by Finland through the Baltic corridor. Importantly, the cost-optimal solution does not include hydrogen imports from outside Europe. This finding underscores that Europe does have the potential to achieve energy self-sufficiency by maximising the use of its domestic renewable resources and developing an interconnected hydrogen infrastructure.

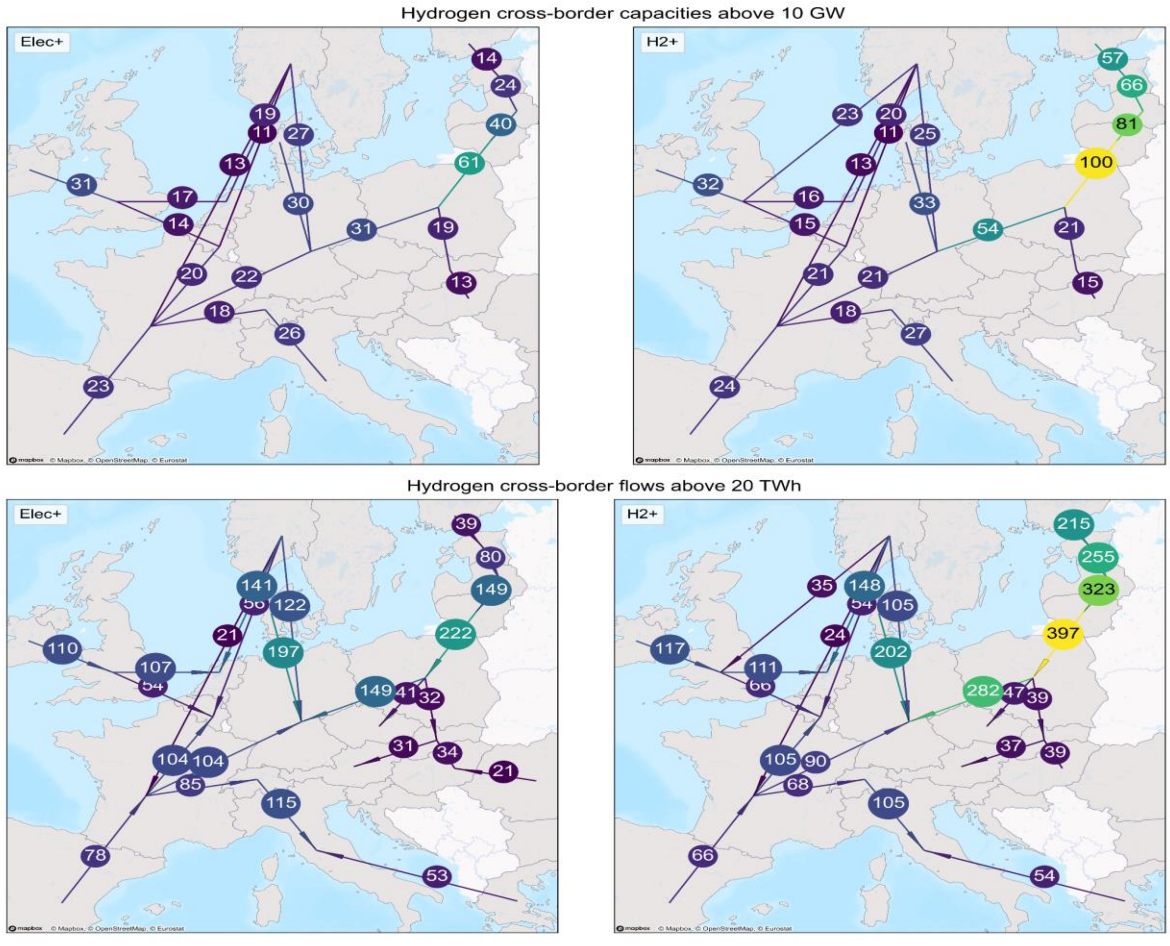

Figure 22: Hydrogen cross-border flows and capacities in the Elec+ and H2+ scenarios

4.2.3 SENSITIVITY WITH IMPORTS OF GREEN BASIC MATERIALS

The Elec+_VC sensitivity assumes that the production of major energy-intensive interim products shifts outside Europe, including iron sponge, ammonia and ethylene (plus other HVCs). As Figure 23 shows, this substantially reduces the energy demand in 2050, by roughly 1270 TWh compared to the Elec+ scenario (not considering the energy content of imports like ammonia or ethylene). This has a major effect on hydrogen demand, which decreases from the 3035 TWh in the Elec+ scenario to 2103 TWh in Elec+_VC sensitivity. See chapter 3 for more details on the driving forces of the demand changes.

These changes in the demand structure result in substantial changes to the electricity supply mix (see Figure 23). Overall generation decreases, but the most obvious change is the reduction of generation from onshore and offshore wind. Offshore wind drops by more than 60%, as it is the marginal supply technology in many countries. Rooftop PV already has only a small share in the Elec+ scenario, and this is even smaller in Elec+_VC. Other supply technologies remain more or less constant between the two scenarios.

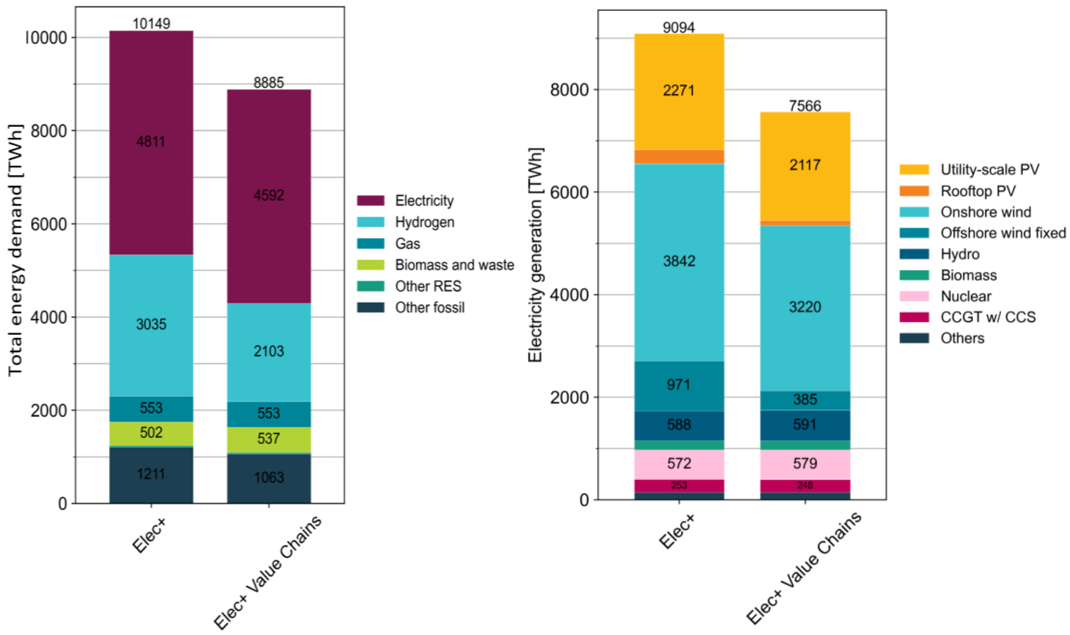

Figure 23: Total energy demand of all sectors (left) and electricity generation (right) in Elec+_VC compared to Elec+

Consequently, the balance of hydrogen production, imports and exports by country is also strongly affected as shown in Figure 24. For example, hydrogen imports in the main importing countries of Germany, the Netherlands and Belgium are substantially lower in Elec+_VC than they are in Elec+. In addition, hydrogen production goes down in the main hydrogen producing countries.

However, the overall pattern of which countries are net exporters or importers is hardly affected:The main transport corridors are still relevant even in the case of reduced hydrogen demand from industry. They are, however significantly reduced in capacity and annual net flow as shown in Figure 25. At the same time, electricity cross-border flows and capacities are hardly affected in the Elec+_VC sensitivity compared to the Elec+ scenario (see annex).

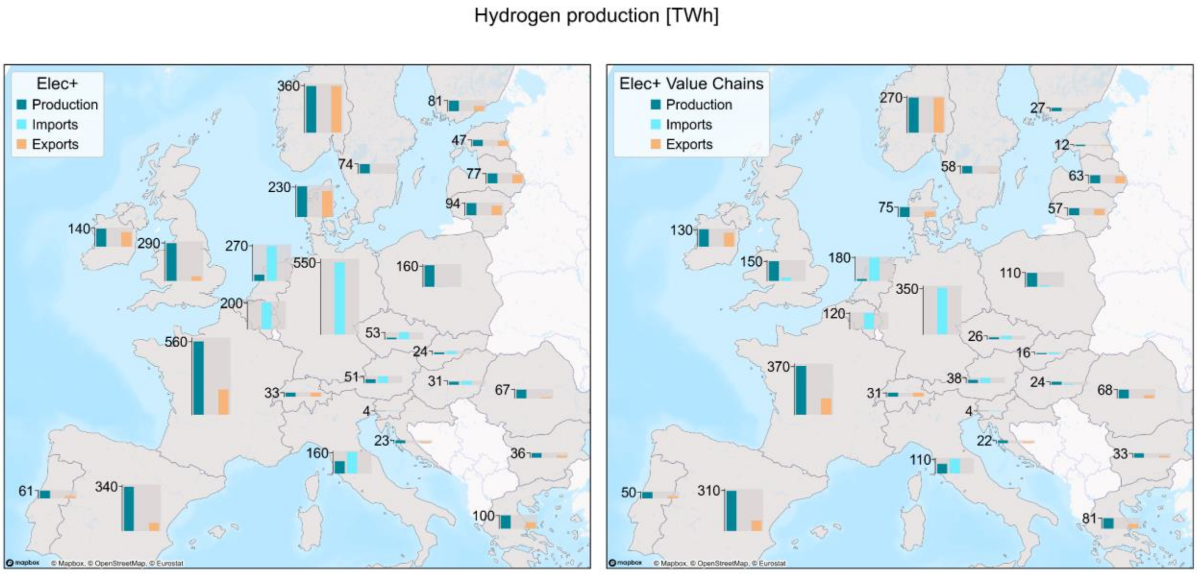

Figure 24 Hydrogen production imports and exports in sensitivity Elec+_VC compared to Elec+ [TWh]

To summarise, the results of the sensitivity analysis show that the EU's CO_2-neutral energy system with hydrogen (and electricity) transport corridors from Europe's large RES potentials towards the centre is not only determined by industrial structure. It is still part of a cost-effective solution even with substantially less heavy industry in central Europe. To an even greater extent, it seems to be determined by the cost-effective RES potentials in countries like the UK, Nordics, Baltics, Spain and France combined with the cost-effective transport of hydrogen to other countries. This suggests that a hydrogen transport network combined with least-cost RES deployment will form a robust element of a CO_2-neutral energy system in Europe.

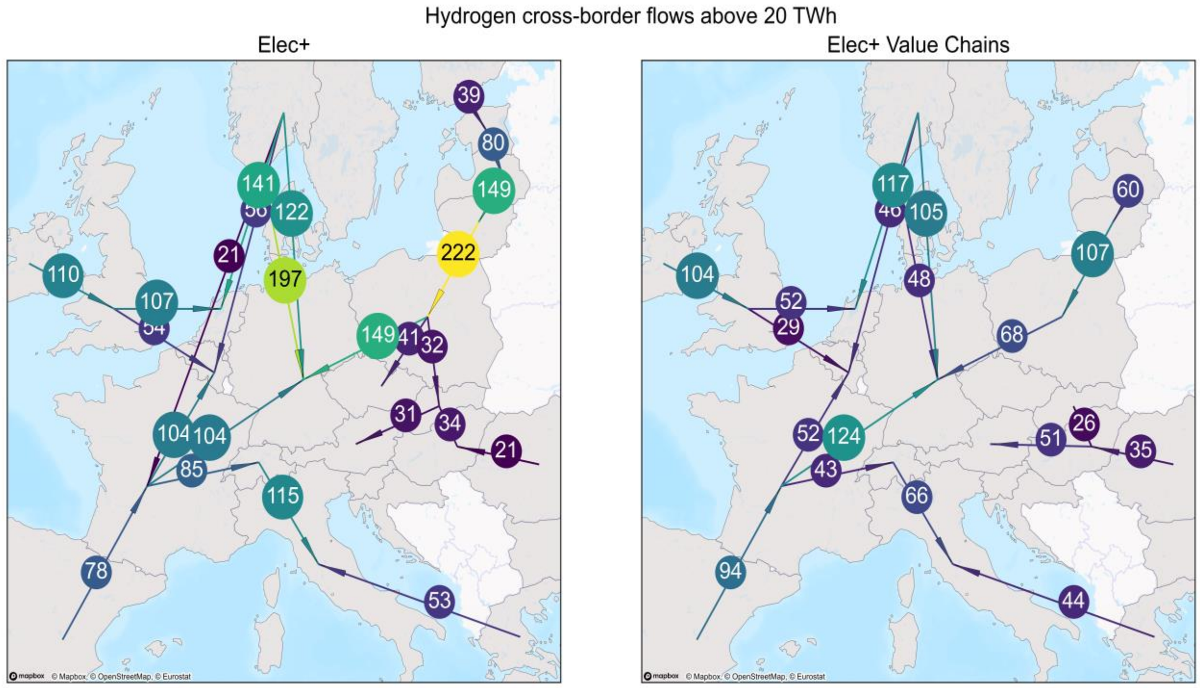

Figure 25: Hydrogen cross-border flows above 20 TWh in Elec+ and Elec+_VC [TWh]

4.2.4 SENSITIVITY ANALYSIS WITH CONSTRAINED RENEWABLES POTENTIALS

The sensitivity H2+_LimPotential examines uncertainties regarding the realisation of total RES potentials. In this sensitivity, changes are only made to the energy supply side, the energy demand is based on the H2+ scenario. The *H2+_limPotential* sensitivity assumes two major changes to RES potentials, which result in RES deployment deviating from the least-cost solution:

1. The first assumption is that at least 20% of the overall rooftop PV potential is deployed in every country. This reflects on the low rate of rooftop PV deployment in the H2+ and Elec+ scenarios due to comparatively high generation costs, which is addressed by governmental plans to support and deploy rooftop PV and the actual trends with high growth rates in many EU countries.

2. The second assumption constrains the assumed wind and PV technical potentials to 70% of their original assumed values by multiplying the entire cost-potential curve by 0.7.In both scenarios, Elec+ and H2+, we have observed very high deployment rates of RES, often up to the maximum potentials in many countries. This limitation is expectted to result in a more balanced RES deployment across Europe.

Both assumptions are intended to reflect that real-life developments might deviate from the cost-optimal solutions calculated in the H2+ and Elec+ scenarios. The sensitivity analysis aims to shed light on how these changes impact the energy system and the need for infrastructure.

As expected, the most visible changes are those in electricity generation and capacity (see Figure 26). The production from rooftop PV increases significantly by an additional 450 GW of installed capacity. However, the overall reduction in electricity generation from wind is only about 10% below the H2+ scenario, which indicates that many countries did not fully exploit the available potentials.

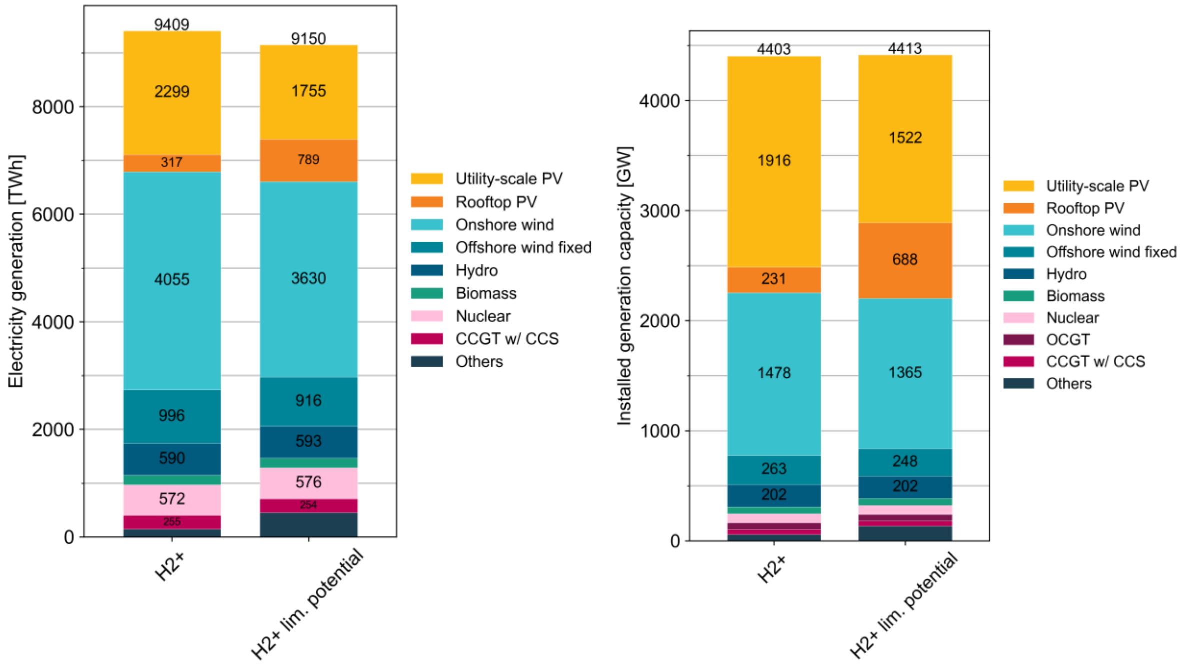

Figure 26: Electricity generation and installed capacity by technology in H2+_LimPotential and H2+ in 2050

An increase in the costs of hydrogen production is one direct consequence of RES deployment that deviates from the cost-optimal solution. More specifically, the average marginal costs of hydrogen production increase by 11% from 61 in the H2+ scenario to 68 EUR/TWh in the H2+_LimPotential sensitivity analysis. The hydrogen flows across Europe are also affected, but the most striking result is the inclusion of 160 TWh of imports from Morocco to Spain in the cost-optimal solution. These imports are still relatively small compared to the 3000 TWh of hydrogen produced in Europe. Larger restrictions on RES deployment would certainly increase both the need for imports as well as the average costs of hydrogen production.

There is also a major effect on the hydrogen flows within Europe. The corridor from Scandinavia to central Europe becomes substantially more important, reflecting the increased RES deployment in Sweden. At the same time, the overall picture of the main corridors remains largely unchanged compared to the H2+ and Elec+ scenarios, underlining their robustness.

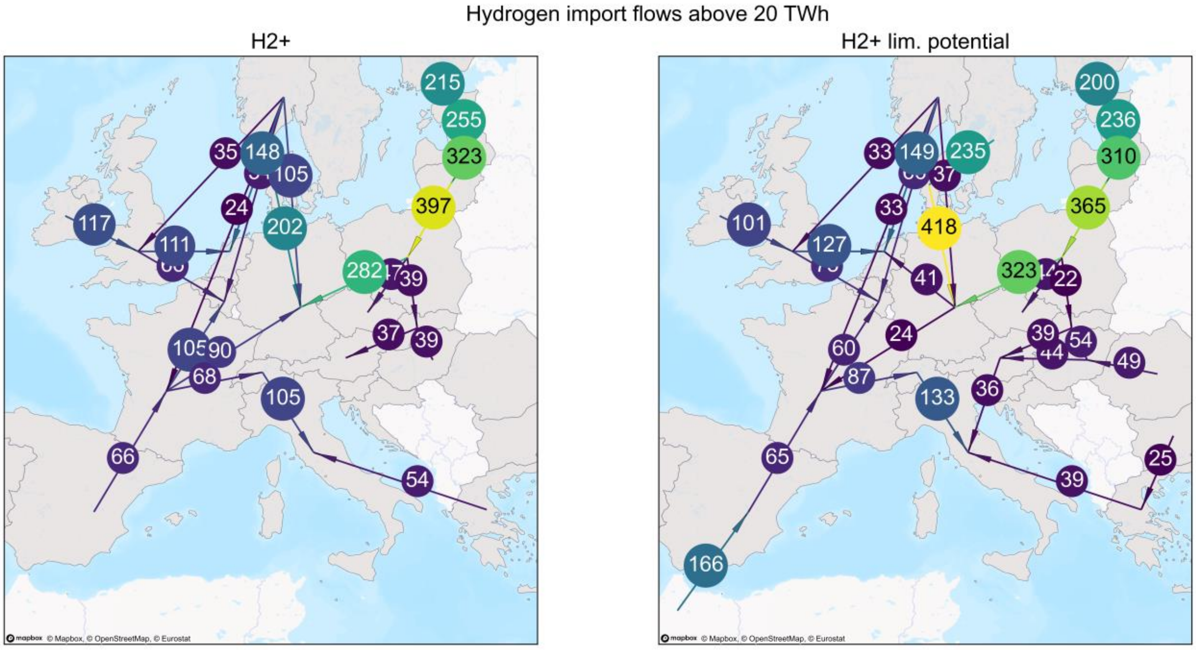

Figure 27: Comparison of hydrogen cross-border flows in H2+_limPotential and H2+ in 2050

5 CONCLUSIONS AND SUMMARY

Our analysis combined a detailed simulation of the transition to a CO_2-neutral industry sector with an analysis of the entire energy system in Europe. We first calculated the energy demand from the industry sector and then fed these results into the energy system model METIS, which uses cost optimisation to calculate the supply and transport of energy for every hour of the year 2050. We defined two scenarios, Elec+ and H2+ plus sensitivities, which placed additional constraints on RES potentials (H2+_limPotential) and industry structure by assuming stronger imports of green basic materials (Elec+_VC). The H2+ scenario differs from the Elec+ scenario only in the degree of hydrogen used in industrial process heat, while all other assumptions are similar.

The following conclusions can be drawn for the transformation of the industry sector based on the first part of the analysis (chapter 3).

1. **GHG reduction of at least 95% is possible in the industry sector by 2050.** A fully net-zero industry might require compensation for the remaining smaller sources of process-related emissions from diverse processes.

2. **Energy and material efficiency and the circular economy are important strategies to reduce the demand for carbon-free secondary energy carriers.** A moderate reduction in FED is still possible even if GDP and industrial value added are projected to grow. However, the potentials for improving energy efficiency are limited, as many energy-intensive processes have already been largely optimised over decades because of high energy costs.

3. **The rapid (before 2030) introduction and broad diffusion of new climate-neutral production processes is required in many sectors.** Due to long lifetimes and modernisation cycles of more than 20 years, the re-investments required in the coming years will need to choose climate-neutral technologies. For example, both scenarios already project more than 10 Mt new production capacity of steel via the direct reduction of iron ore process.

4. **Green electricity and green hydrogen are needed in large quantities to enable low-carbon production.** By 2050, hydrogen and electricity dominate the energy supply of a climate-neutral industry sector (~80%). Biomass, ambient heat and district heating also contribute, but with substantially smaller shares.

5. **Electricity becomes the most important energy carrier and the demand for it grows in both scenarios.** The electrification of process heat overcompensates efficiency gains in other end-uses resulting in an overall increase in electricity demand. In Elec+, process heat adds about 800 TWh on top of the demand from other processes, resulting in a total of 1854 TWh by 2050. In H2+, hydrogen is used to supply process heat to a greater extent, reducing the additional electricity demand to 477 TWh. Despite this, the H2+ scenario still shows a strong increase in overall electricity demand from today's 1,050 TWh to 1,528 TWh by 2050 with some “no-regret” electrification options like efficient high-temperature heat pumps for steam generation.

6. **Hydrogen and/or its derivatives are required for low-carbon production in chemicals and steel but also process heat.** Even in the Elec+ scenario, there is a substantial demand for hydrogen of 1,343 TWh by 2050, mainly due to hydrogen use as a feedstock for low-carbon chemicals and for steel production via the direct

reduction route. In the H2+ scenario, hydrogen demand even rises to 1,785 TWh by 2050, as hydrogen is used to supply process heat to a greater extent.

7. **If parts of the chemical value chain are offshored and products like green methanol, ammonia or ethylene are largely imported, the demand for domestic hydrogen from Europe's industries could be drastically lower.** The Elec+_VC sensitivity assumes that large production shares of major energy-intensive products shift outside Europe, including iron sponge, ammonia and ethylene (plus other HVCs). Under these assumptions, hydrogen demand from industry drops to 416 TWh, only one third of the demand in the Elec+ and H2+ scenarios. This underlines how sensitive hydrogen demand from industry is to the developments of only a few main energy-intensive products.

The energy systems analysis was based on a strict techno-economic optimisation with as few limitations as possible. It considered renewable energy potentials and costs by country based on a detailed analysis of land-use structures. The deployment of renewables, electrolysis and other supply technologies was not restricted. Cross-border electricity transmission capacities were restricted according to the planned transmission capacities in the TYNDP (ENTSO-E), while capacities for hydrogen cross-border flows were not limited. Based on these assumptions, the system analysis leads to the following main conclusions.

1. **The massive increase in demand for electricity and hydrogen shapes the energy system.** While overall energy demand decreases from roughly 13,100 TWh in 2019 to roughly 10,000 TWh in 2050 due to efficiency gains in buildings and transport, there is substantial increase in the demand for electricity and hydrogen. Starting from 2,876 TWh in 2019, electricity increases to 4,232 TWh (H2+) and 4,556 TWh (Elec+). Hydrogen demand increases to 3,035 (Elec+) and 3,488 TWh (H2+) by 2050. Together, these two energy carriers account for nearly 80% of overall energy demand by 2050.

2. **From a techno-economic perspective, renewable energy sources have the potential to meet Europe's energy demand at competitive costs (with the exception of some imported synfuels).** Solar and wind potentials are utilised massively and allow fully domestic production of hydrogen and electricity in this cost-optimised system. By 2050, wind and solar energy together account for nearly 80% of domestic EU electricity production, which totals 9,100 (Elec+) and 9,410 (H2+) TWh. Wind alone supplies between 4810 TWh (Elec+) and 5,050 TWh (H2+).

3. **Domestic hydrogen production is available at a lower cost than those assumed for H_2 imports; imports of hydrogen via pipeline from MENA only become cost-competitive if RES deployment is sub-optimal/constrained.** In the two main H2+ and Elec+ scenarios, hydrogen imports are not part of the cost-optimal system. When limiting RES-potentials to 70% of their original values in each country, domestic hydrogen production costs increase by 11% and non-EU hydrogen imports in least-cost segments become part of the cost-optimal solution.

4. **Hydrogen, produced using large-scale RES in various EU countries with high RES potentials, is transported to central European industrial clusters via the European hydrogen transport system.** In a cost-optimal system, RES capacities are strategically located in regions with high load factors, and the generated energy is then transported to the demand centres in central and northwestern Europe. Electrolysers are built close to these RES generation centres and hydrogen is transported to the demand centres. The scenarios show very limited to virtually zero electrolyser capacities in countries like Germany, Belgium, the Czech Republic and the Netherlands. This is also confirmed by the fact that there is only a slight increase in domestic RES generation in the H2+ scenario compared to the Elec+ scenario (roughly +300 TWh). The greater use of hydrogen in the H2+ scenario allows better long-distance transportation of energy and thus better exploitation of least-cost RES potentials.

5. **A pan-European hydrogen network is essential:** The results show that robust hydrogen corridors connect the Nordics, Baltics, the UK, the Iberian Peninsula and France with Germany, Benelux, Austria and Italy. Even in cases of low domestic industrial demand or limited RES potentials, these hydrogen transport corridors remain part of the cost-optimal solution. They are driven more by differences in RES generation potentials and costs than by high demand from industry.

6 ANNEX

6.1 THE INDUSTRY SECTOR MODEL FORECAST

The integrated modelling platform FORECAST is a comprehensive and robust strategic decision support tool, primarily designed to develop detailed long-term scenarios for energy demand, greenhouse gas emissions, and decarbonisation strategies for the industry sector. It considers a broad range of mitigation options combined with an explicit focus on a high level of technological and geographic detail, as outlined in (Fleiter et al. 2018). The platform's ability to explicitly consider technology diffusion and stock turnover is key to its function of offering valuable insights into potential transition pathways and their associated timelines. FORECAST also aims to integrate policies and consider changes to the socio-economic framework.

One of FORECAST's significant strengths is its strategic combination of both bottom-up and top-down methodologies that results in a well-rounded perspective on the sustainable transition of industry. The bottom-up approach in the FORECAST model ensures a high level of technological detail. It delves deep into the industrial sector, its specific processes and technologies, and comprehensively assesses a wide range of mitigation options. Simultaneously, the top-down approach in FORECAST closes knowledge gaps and calibrates the model to align with energy balances and larger economic and policy dynamics.

The model is designed to cover the entire industrial sector according to the Eurostat energy balances, which encompass eight separate industries defined by the NACE 2 classification. These include both energy-intensive (iron and steel, chemicals, non-metallic minerals and others) and less energy-intensive sub-sectors. This structure enables detailed simulations of individual sub-sectors and applications, providing valuable insights into each domain. The model's scope is defined by the energy balances (Eurostat) with a focus on final energy, but it also accounts for useful energy.

FORECAST's integrated modelling platform strategically utilizes a wide range of input data. These are drawn from a wide range of relevant databases and resources and are carefully organised and updated annually in the platform's extensive model database. The comprehensive data include economic and physical indicators, such as sectoral Gross Value Added (GVA), energy prices, and production statistics that shape energy demand and emission trajectories (Figure 28). The model also includes data related to existing policy measures, such as the EU Emissions Trading System (EU ETS) and forthcoming ones that directly influence energy demand and emission trajectories. Furthermore, structural details and technical specifications provide a granular view of the industrial sector, encompassing information about facilities, their age, technologies in use, and detailed technical parameters of current and prospective technologies. These also include short-term factors such as business cycles and temperature (heating degree days) that can affect energy demand within a one-year horizon. By combining detailed economic and physical drivers, structural and technical specifications with broader policy, regulation and behaviour patterns, the model delivers a nuanced understanding of the complexities involved in industry decarbonisation. In this way, it can generate robust and realistic scenarios that aid policymakers and industrial stakeholders in making strategic decisions for a sustainable industrial future.

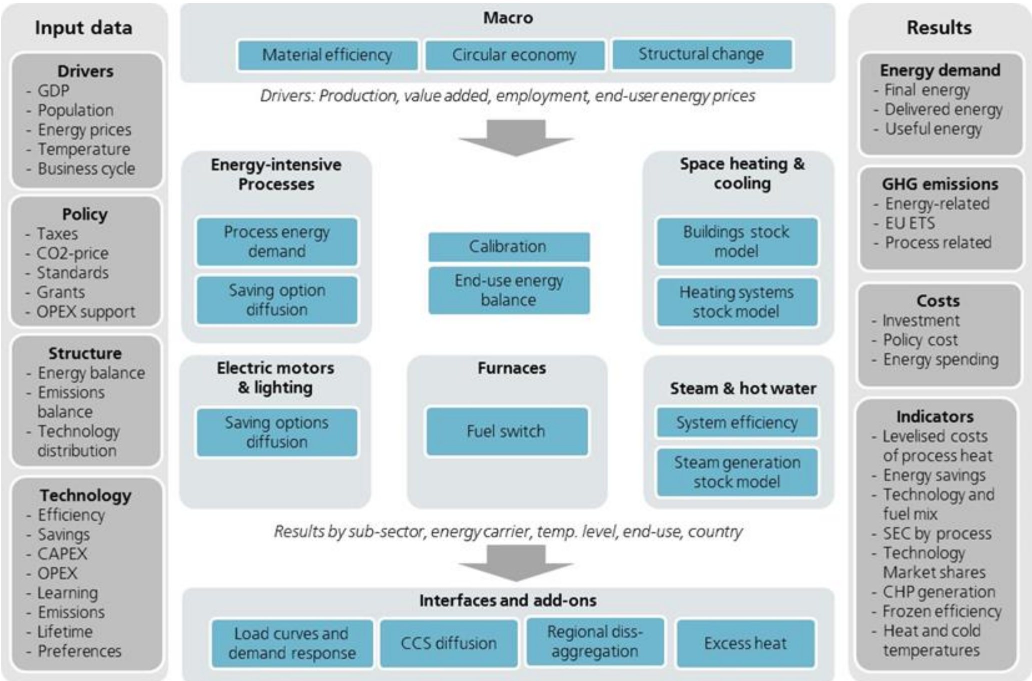

Figure 28: Overview of the FORECAST model: Input data, methods and sub-models (Source: Fleiter et al. (2018)

The model is calibrated using the most recent EUROSTAT statistics for parameters such as energy balances, employment, value added, and energy prices. In cases where EUROSTAT data are unavailable, particularly energy carrier prices, supplementary data are taken from the International Energy Agency (IEA) and other reputable sources to fill the gaps. This data-based approach can accommodate a broad spectrum of different scenarios of prospective developments.

Industrial statistics and future production quantities at process and country level (e.g. electric steel production in Italy) comprise a major input. These are collected and updated annually using a variety of data sources including PRODCOM, UN commodity production database, US geological survey, UNFCCC, and industry organisations (World steel association, CEPI, Cembureau, Eurochlor, etc.).

Technology data (costs, efficiencies, age distribution etc.) are generally not available from public data sources, but need to be gathered from the literature or estimated in consultation with industry representatives. The technology database is continuously improved by individual research projects.

Figure 29 provides an overview of the level of technology detail included in FORECAST. For a complete list of all the technologies included in FORECAST, we refer the reader to the supplementary material in the respective publication.

For a more detailed model description, we refer to (Fleiter et al. 2018) and (Rehfeldt et al. 2020).

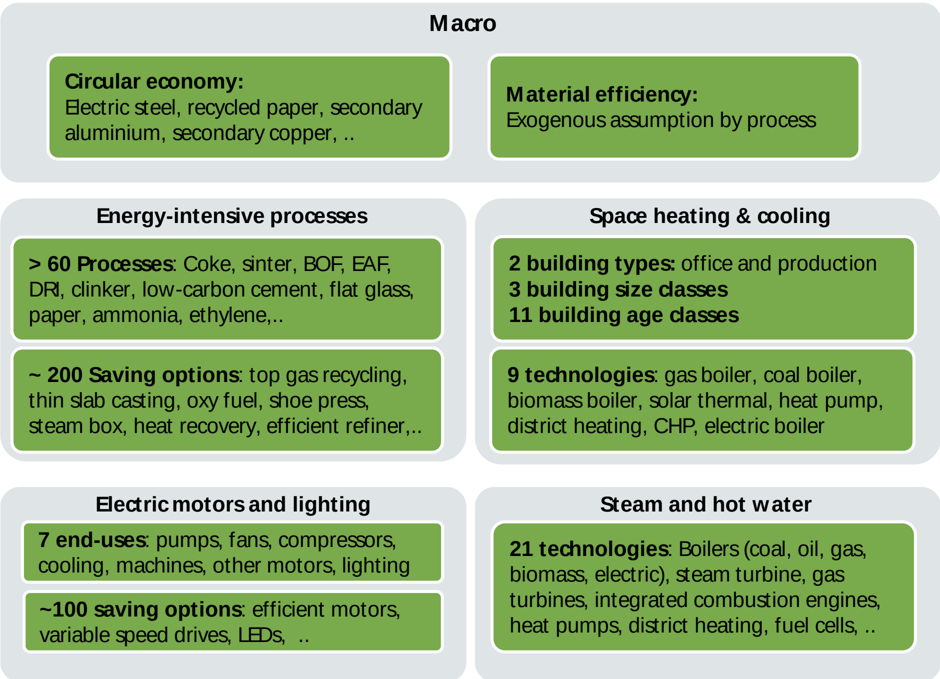

Figure 29: Overview of technology detail in FORECAST by sub-model

6.2 ADDITIONAL RESULTS

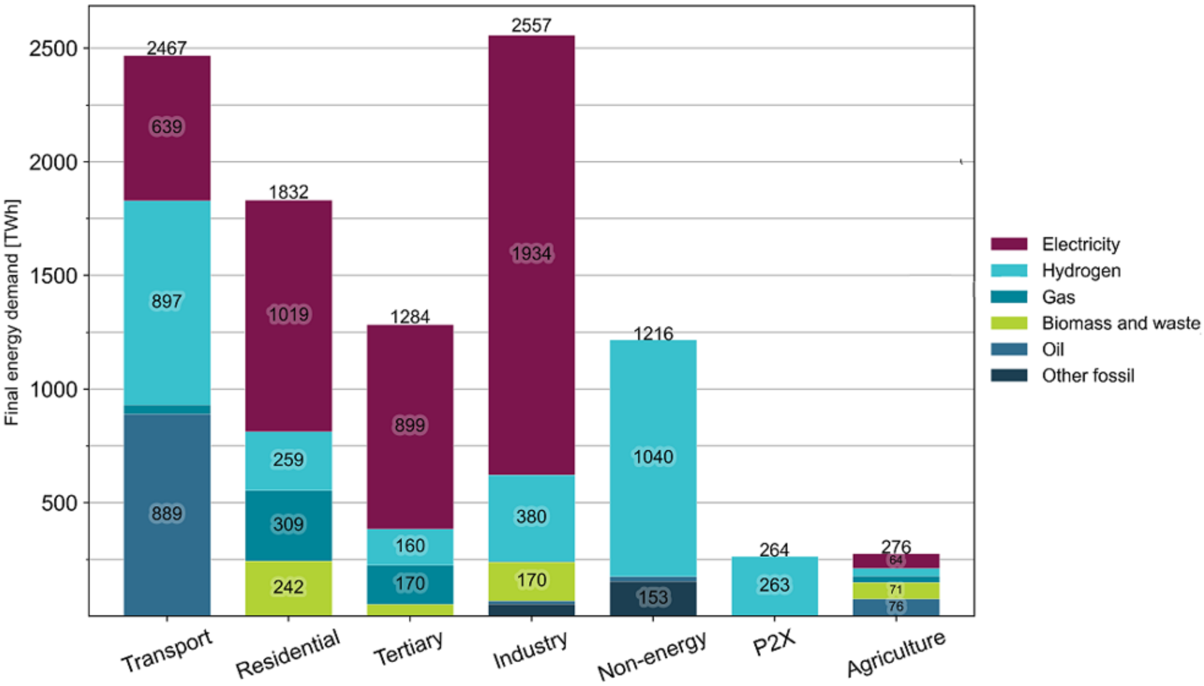

Figure 30 Total energy demand by sub-sector and energy carrier for the modelled countries in Elec+

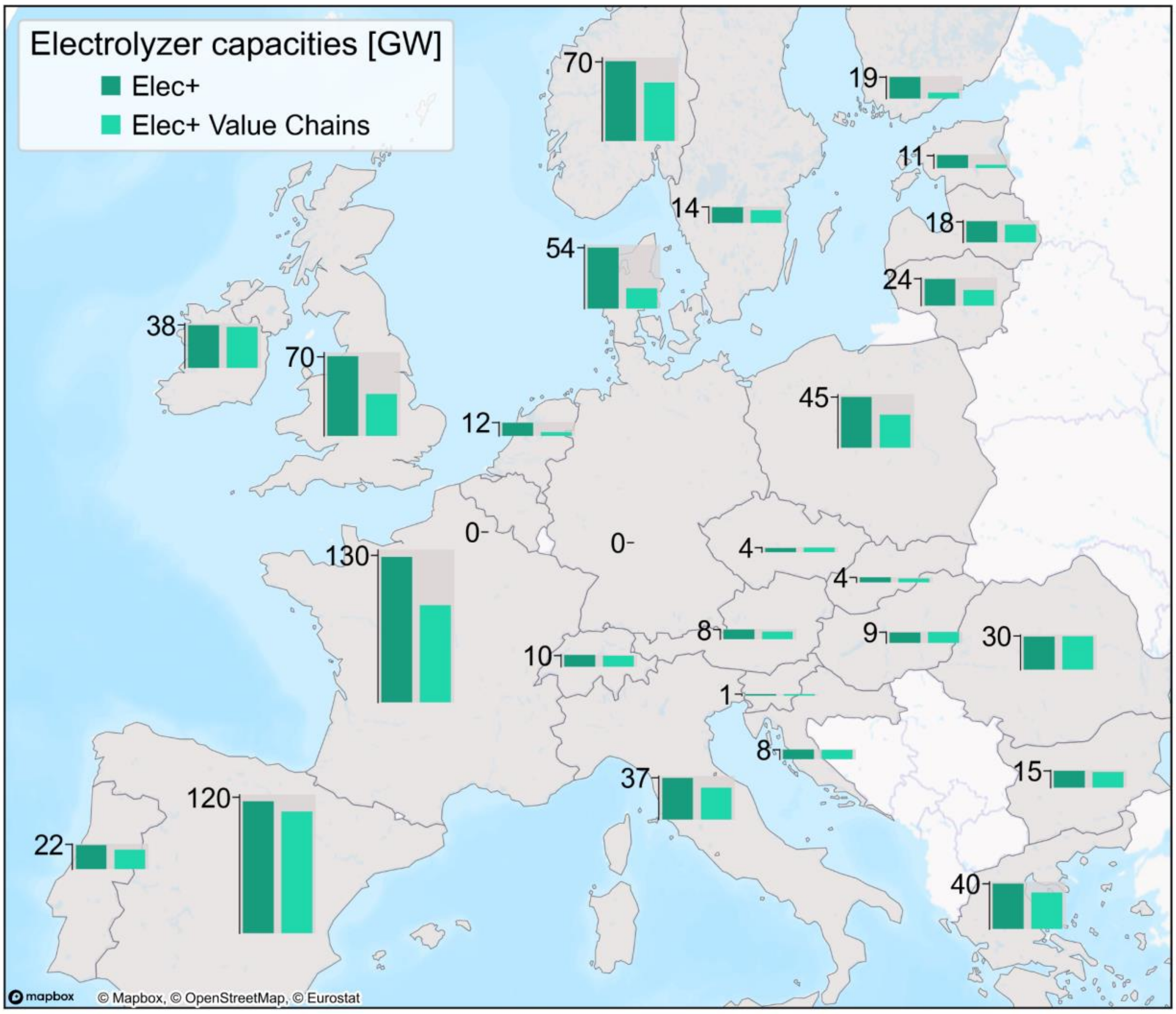

Figure 31: Electrolyser capacities in sensitivity Elec+VC compared to Elec+ [GW]

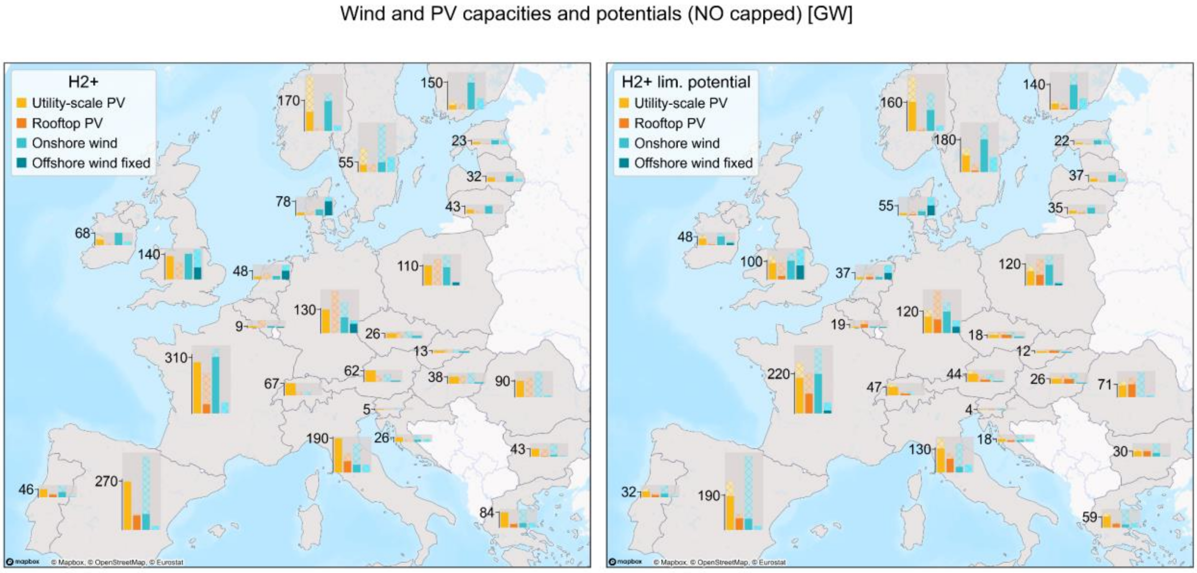

Figure 32: RES potentials and deployment by country in H2+ (on the left) and H2+_limPotential (on the right) in 2050

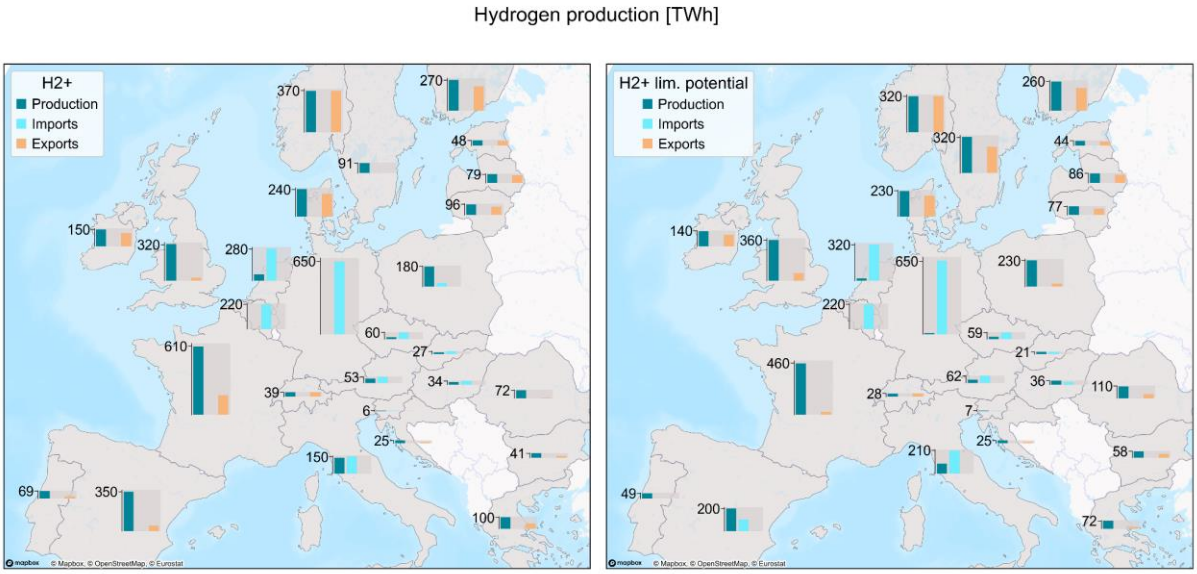

Figure 33: Resulting hydrogen production, imports and exports in H2+ (on the left) and H2+_limPotential (on the right) in 2050

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