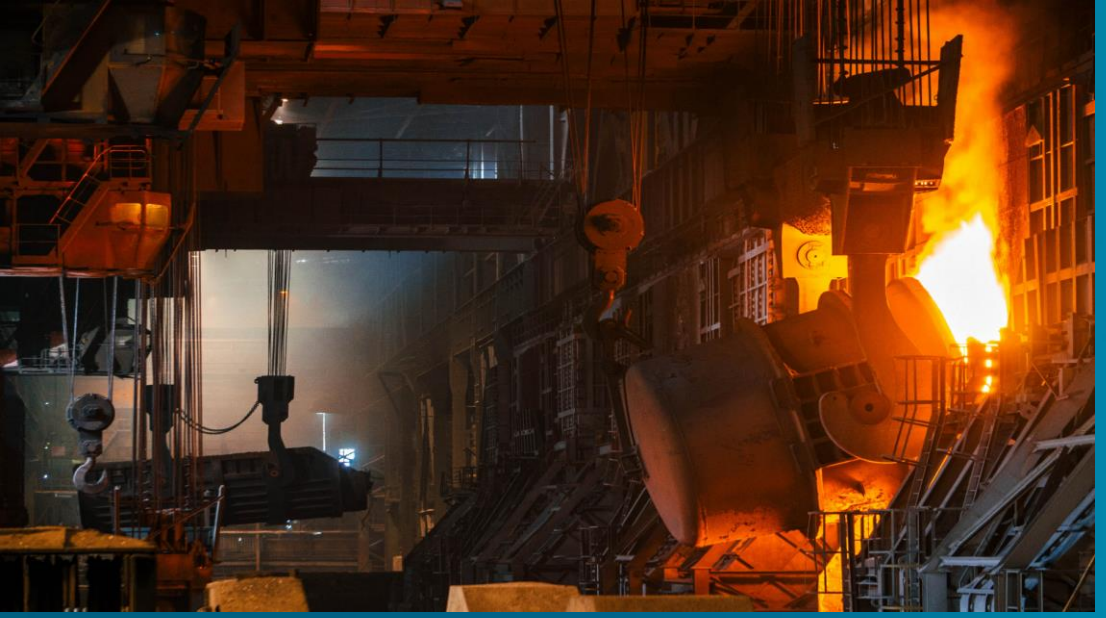


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Fraunhofer Institute for System and Innovation Research (ISI)

2024-01-29

The impact of industry transition on a CO2-neutral European energy system

Agenda

Introduction: Overview of Methodology and Modelling Framework

Scenario definition: Industry and Energy sector key assumptions

Results: Key results from the models (FORECAST and METIS3)

Conclusions: Summarizing key findings

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Methodology

Input parameters | Computation | Results analysis

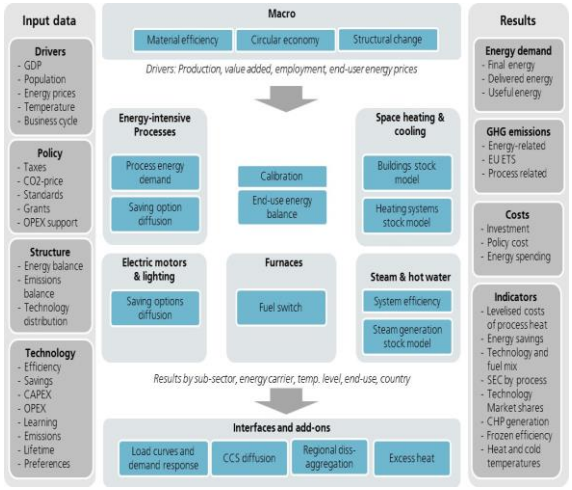
Data Collection & Analysis

- Techno-economic characteristics of Supply , storage and Demand side technologies
- Renewable energy Profiles and potentials
- Data disaggregation and integration in models

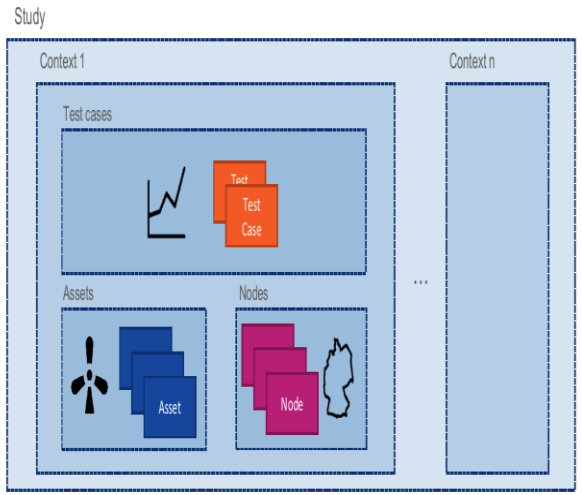
Scenarios Definition

- Energy efficiency
- Material efficiency
- Circular economy assumption
- Technology Diffusion
- Demand Projections
- CO2 and commodity prices

Modelling Industry sector Simulation (FORECAST)



Modelling Supply sector Optimization (METIS 3)



Results analysis

- RES Investments
- Infrastructure Investments
- Operation Management of power, hydrogen and gas systems

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FORECAST tool in a nutshell

Bottom-up modelling of energy demand & GHG emissions

›High technology resolution

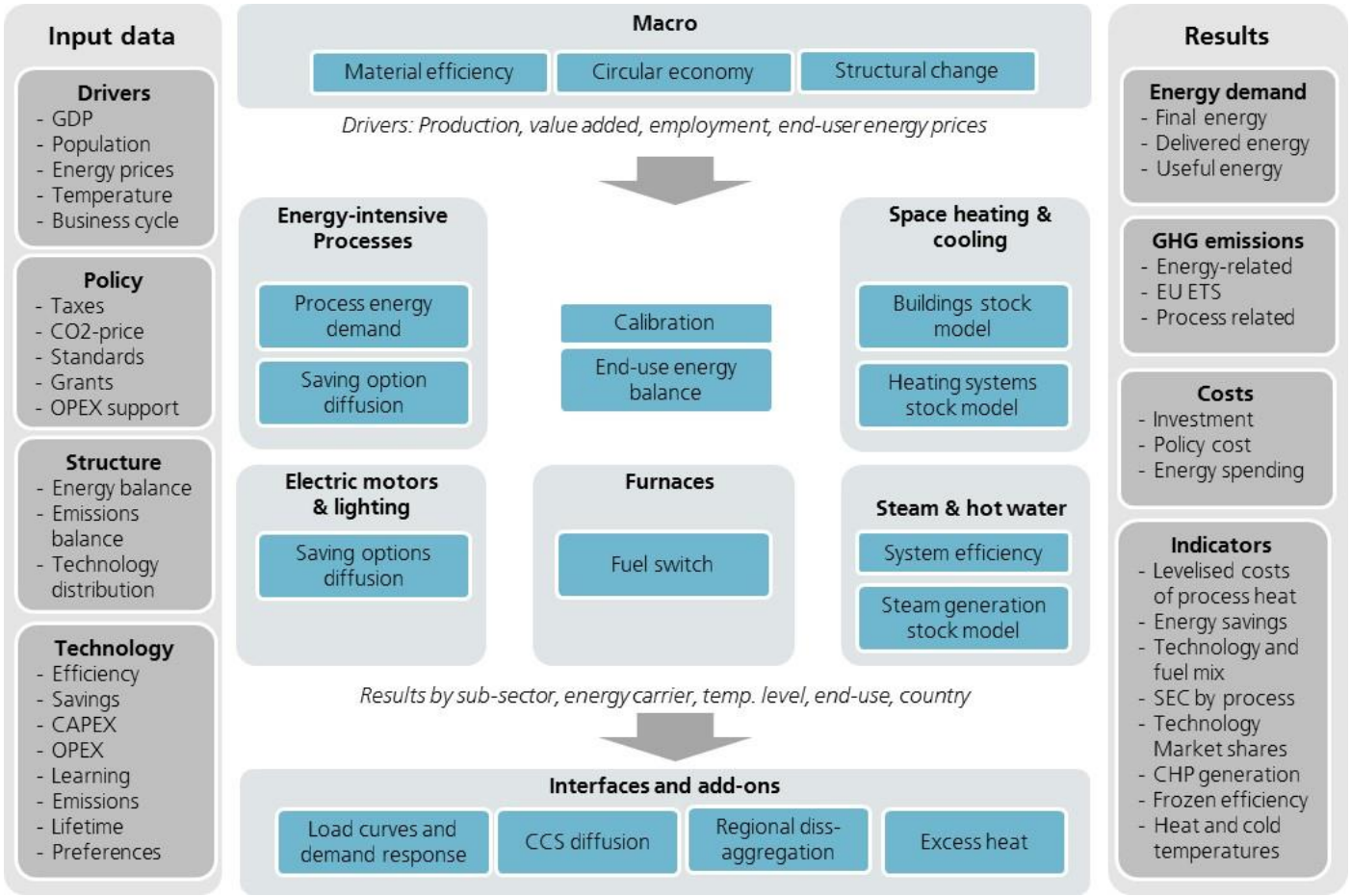
›Consideration of all **important abatement options**

›Energy and greenhouse gas balance

›Annual results
until 2050

FORECAST
FORecasting Energy Consumption Analysis and Simulation Tool

https://www.forecast-model.eu

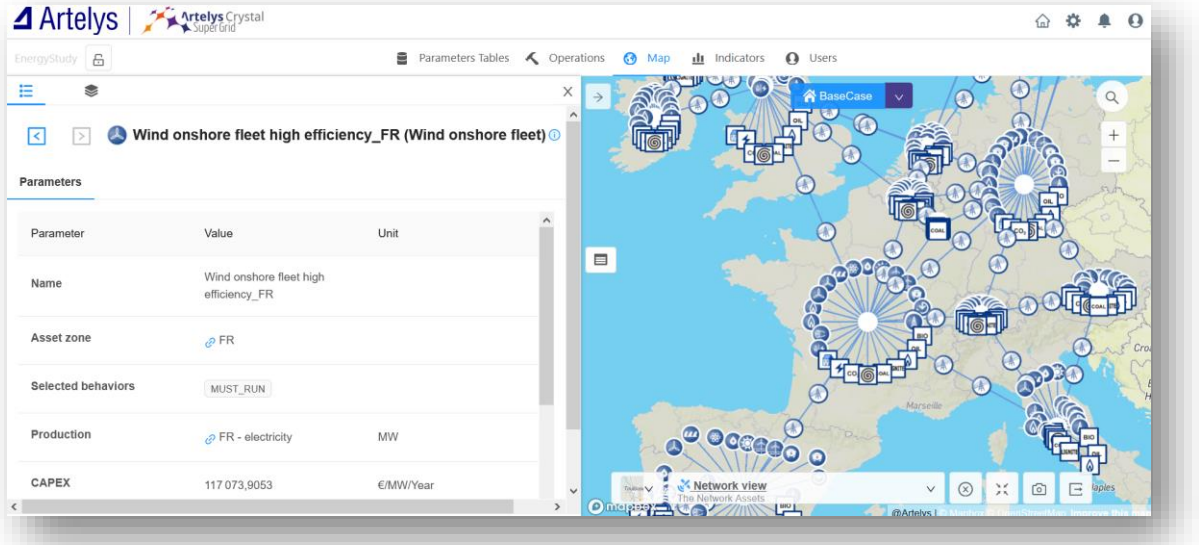


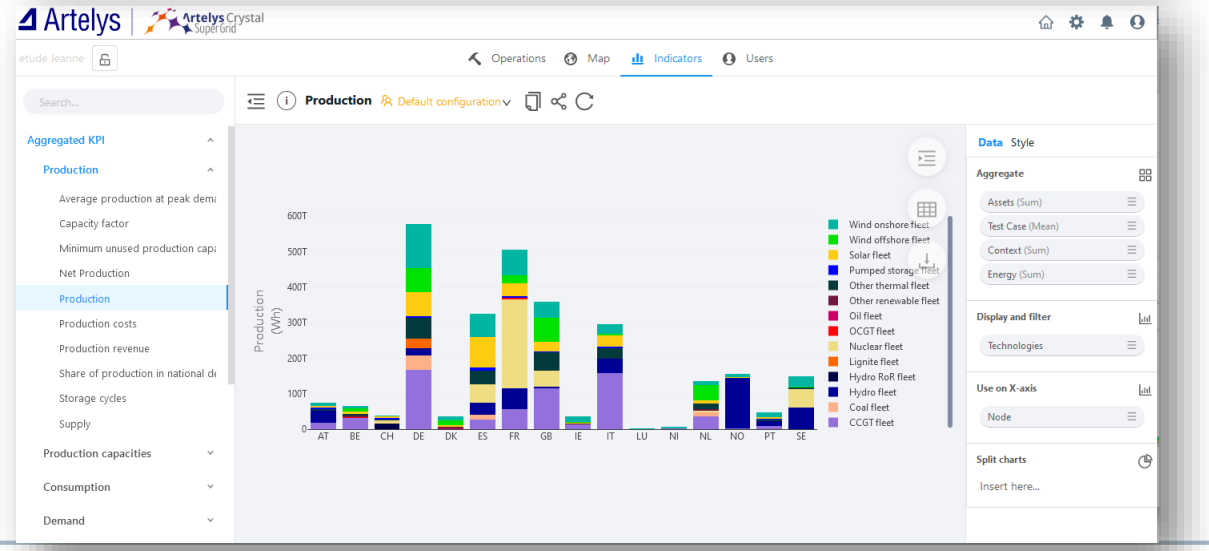
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The METIS tool in a nutshell

- METIS software features
  - Covers **electricity, gas, hydrogen** and heat
  - Includes **EU27 + neighbours**
  - Joint **capacity expansion and dispatch** optimisation
  - Target function: **Minimum overall system costs**
  - **Hourly** granularity, covering an **entire year**
  - Focus on a **given year** or **pathway modelling**
- Not yet covered:
  - Hydrogen derivates and PtX production
  - Regional split beyond country-level





METIS builds upon the *Artelys Crystal Super Grid* platform
https://www.artelys.com/crystal/super-grid/

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Model and scenario setup

Model Set-up

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

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

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

Definition of scenarios

Scenario H2+ (Focus hydrogen): Hydrogen as major decarbonisation option for feedstocks and process heating, while electrification of process heating also has a role, particularly in lower temperature supply of process heat.

- **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): Stronger focus on electrification for decarbonisation of process heat, where technically mature at least at TRL5.

- **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

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Industry sector assumptions and scenario definition

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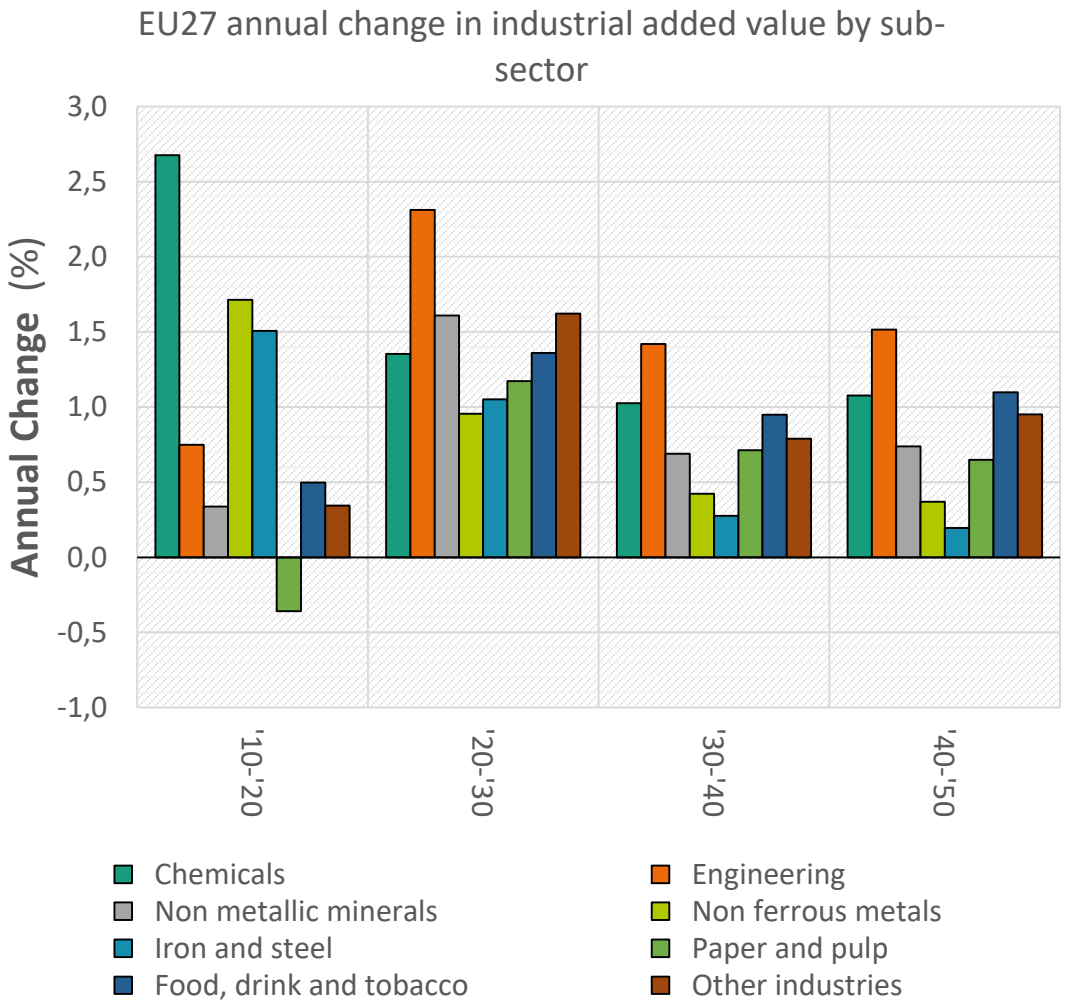
Both scenarios assume continuous economic growth

Value added by sub-sector is the main macro-economic driver for the scenarios

Both scenarios use similar assumptions based on Primes Mix-H2 scenario:

An average annual growth rate in (gross) value added of around 1.3% p.a. is assumed for industry until 2030, afterword's the growth rate declines to 0.7% p.a.

Engineering, food and other industries are projected to be growing at a higher pace compared to the energy-intensive basic materials industries



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Scenarios assume continuous economic growth

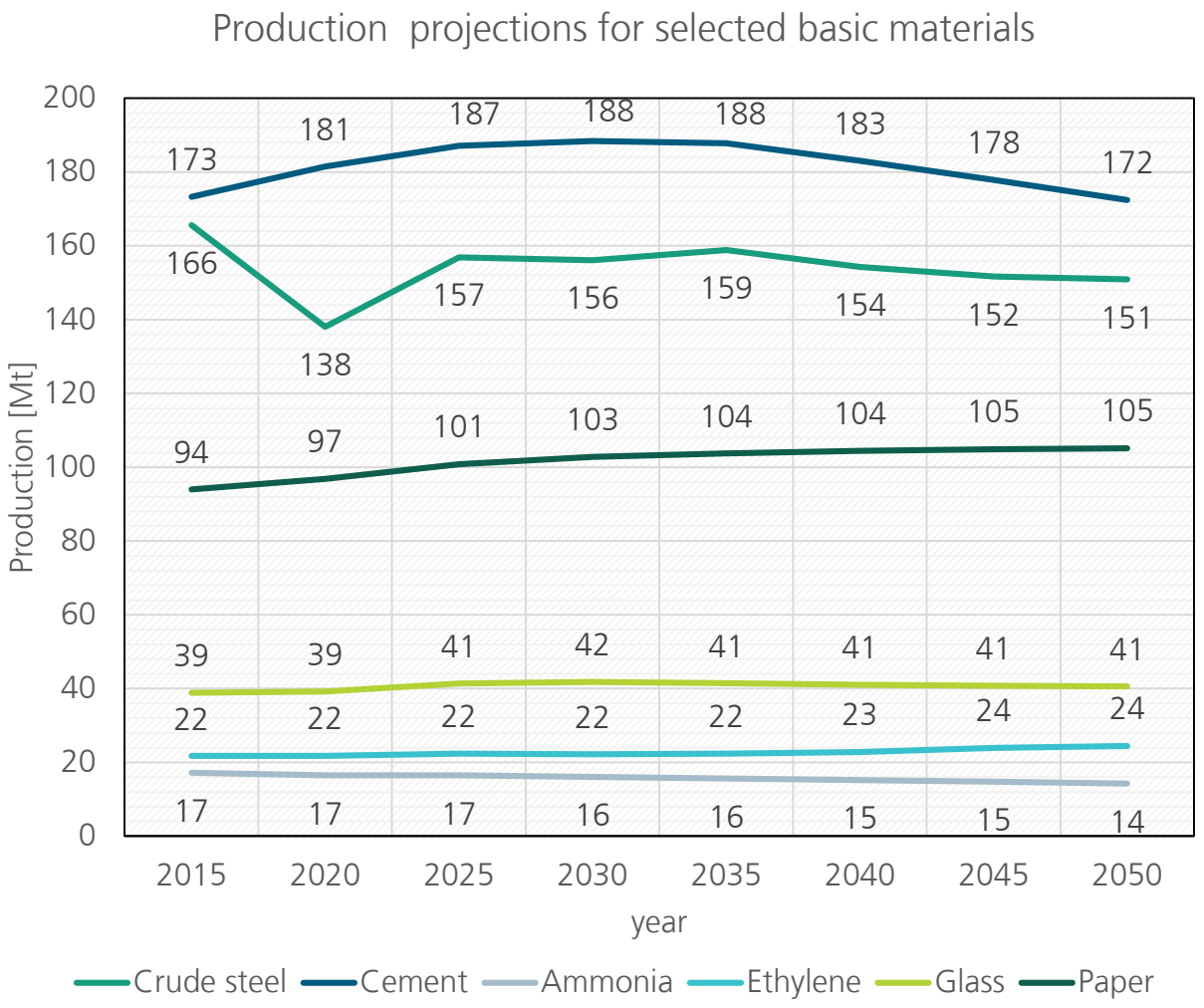
Assumptions

Value added: All scenarios use similar assumptions based on the Primes Fit-55 scenario:

- An average annual growth rate in (gross) value added ~1.3 % p.a. until 2030, afterwords lower at ~0.7% p.a.
- Engineering, food and other industries are growing at a higher pace compared to the energy-intensive basic materials industries

Physical production: Continuous development assumed of more than 50 individual products

- Some products show a decrease in the long-term driven by material efficiency (Diagram on the right)



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Overview of key scenario and sensitivities assumptions for industry

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 Fit-55 (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 & material efficiency	Ambitious progress			
CCS and CCU	Included for cement and lime plants only			
Process, fuel and feedstock switch	Priority hydrogen		Priority electrification	
Relocation of basic materials plants	Domestic production of green basic materials at today's locations			Import of sponge iron, green ammonia and HVCs
Renewable energy potential	Technical potential	Limited technical potential	Technical potential	

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Material efficiency and Circular Economy reduces demand for basic material

Assumptions

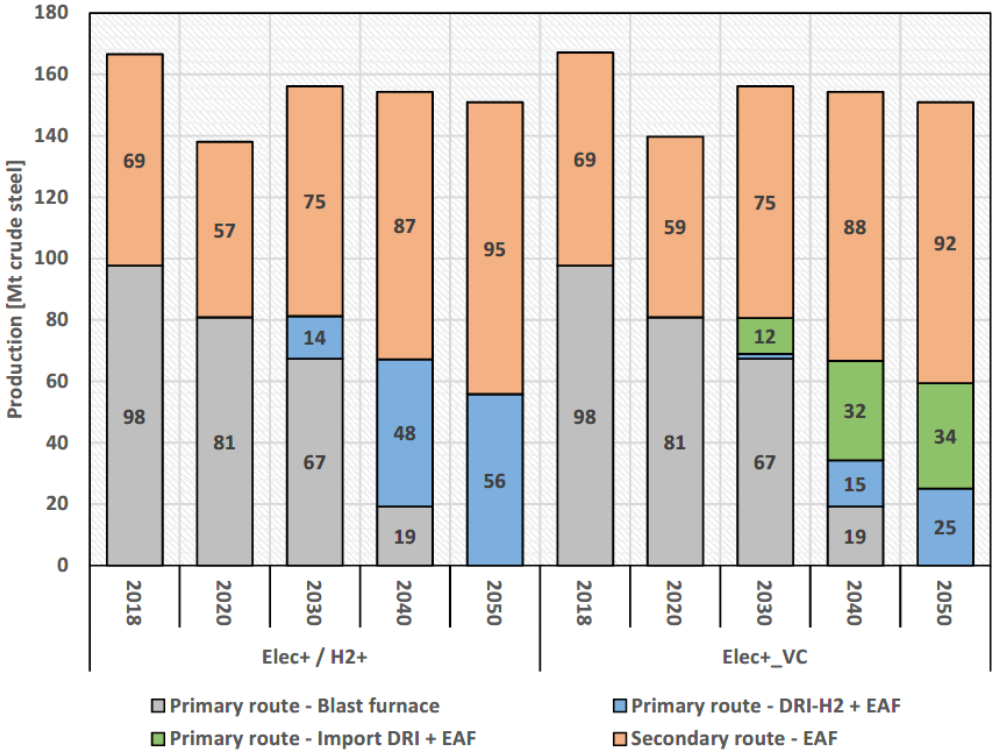
Product	Material efficiency and demand assumption	Circular economy assumption
Steel	More efficient steel use and substitution result in decrease in production	Increase secondary steel share from 41% (2018) to 59% (+25 Mt) by 2050
Chemicals	Plastics substitution, reduced fertilizer demand and more efficient material use	~20% increase in mechanical recycling compared to today
Cement and lime	20% decrease in the clinker share, efficient concrete use and substitution results in decrease in production Reduced demand for lime from blast furnace and power plants	No secondary production route available
Glass	13% decrease in container glass as result to more efficient use	Increase flat glass recycling
Paper	Structural change: Reductions in graphic paper are overcompensated by packaging demands	Recycling share increases in some countries, but relatively saturated market

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Iron and Steel: Full diffusion toward Hydrogen direct reduction by 2050

Assumptions

	H2+ / Elec+	Elec+_VC
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 Hot Briquetted Iron (HBI)

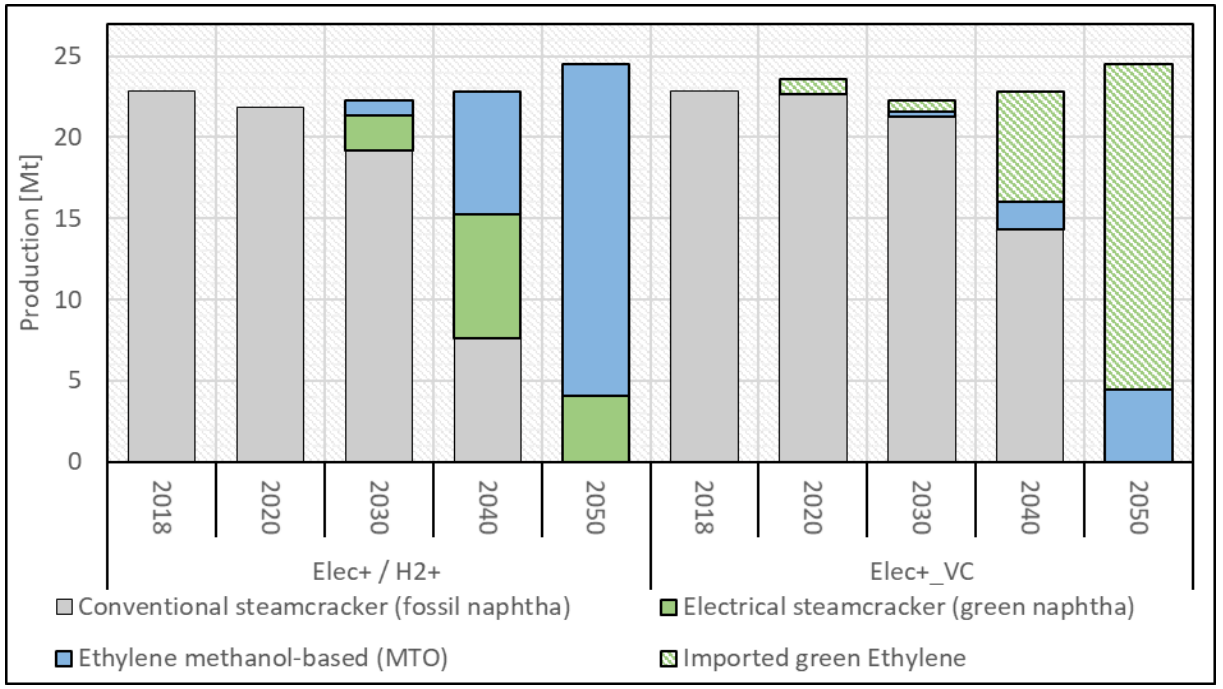


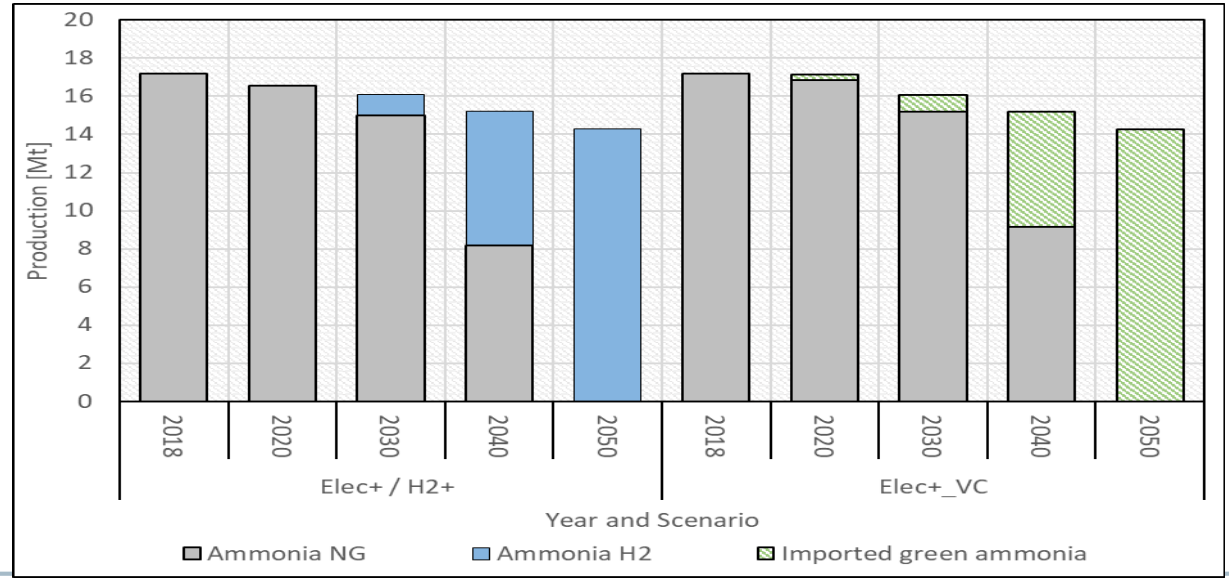
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High-Value Chemicals and Ammonia

Assumptions

	H2+ / Elec+	Elec+_VC
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





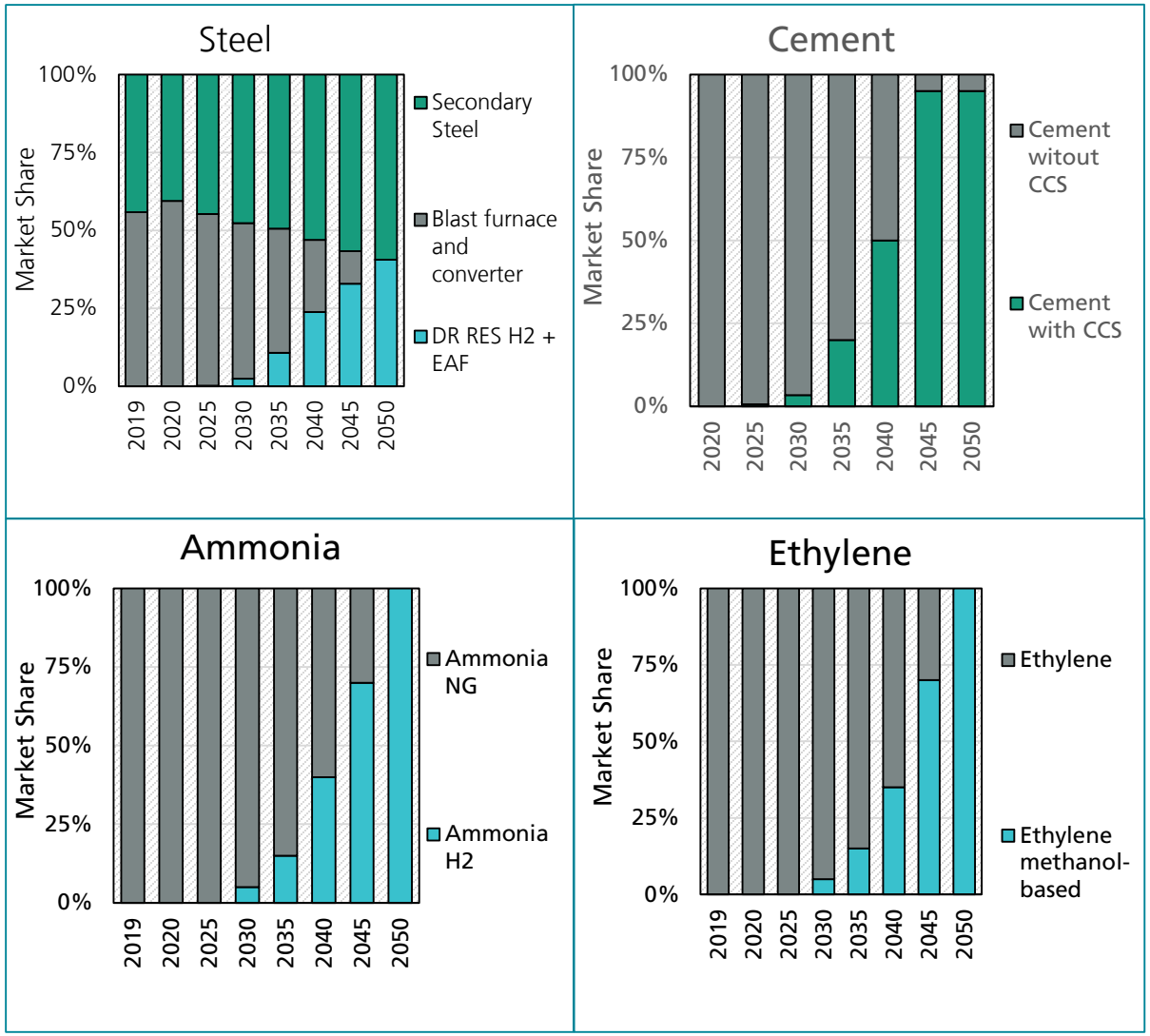
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Process switch: Full diffusion of low-carbon processes by 2050

Assumptions

Product	Elec+	H2+	Elec+_VC
Steel	100% of H-DR share of primary steel by 2050		A limited shift toward H2-DRI (25 Mt) and 34 Mt import of HBI
Chemical feedstocks	100% Feedstock H2 for Methanol, ethylene/HVCs, ammonia and other feedstocks		Ethylene: Import of green ethylene and limited domestic production via MTO (4Mt) Ammonia:100% of the EU's demand will be imported
Cement and lime	Strong diffusion of CCS reaching ~90% of production capacity by 2050 Slow increase in low-carbon cements to ~10% market share by 2050 (new binders)		
Glass	70% Electric furnaces by 2050	Higher share of hybrid furnaces	= Elec+
Steam generation	Electric boilers and heat pumps, limited biomass	H2 boilers, hybrid boilers, electric heat pumps, limited biomass	= Elec+



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Industry sector results

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Circular economy: A key to lowering demand for carbon-free secondary energy carriers

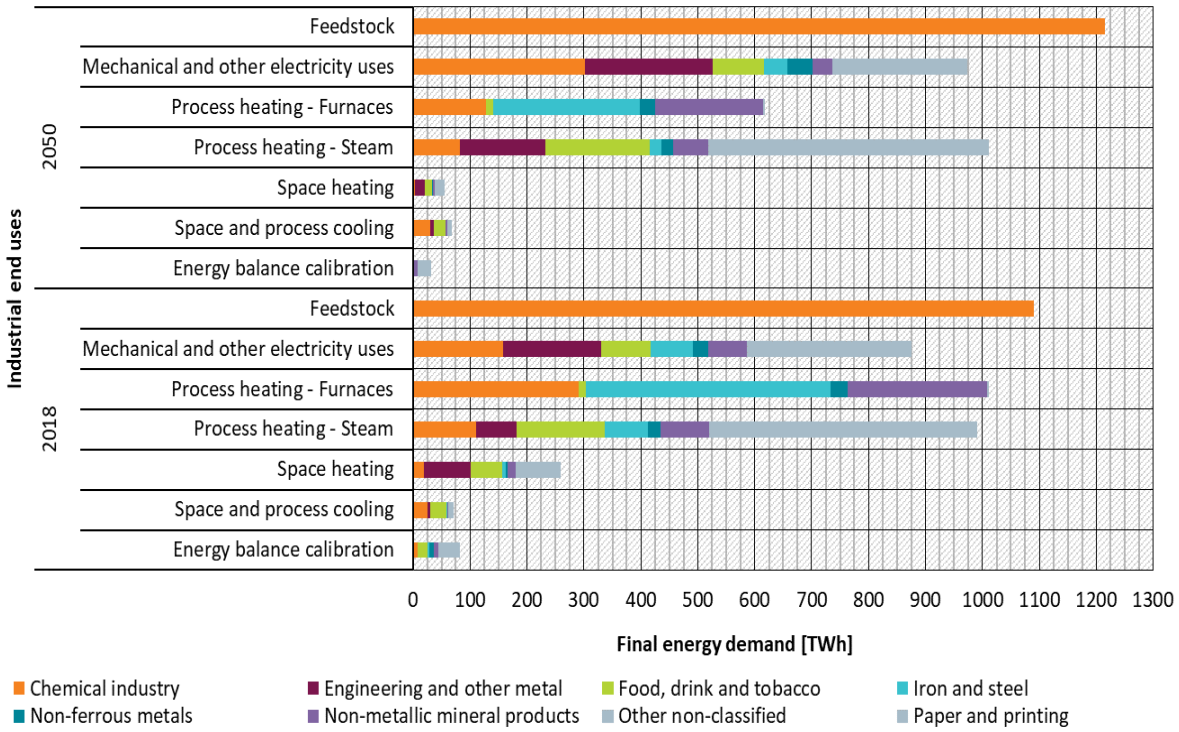
Results: Total industrial energy demand by end use

In 2018 Total energy demand (TED) for industry in the EU 27 + UK = 4,408 TWh

The **chemical industry** accounts for the highest energy demand **(39% of TED)**, followed by the **iron and steel industry (14%).**

Process heating is the largest end-use with about 2000 TWh of energy

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



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Industrial transformation requires high quantities of CO2-neutral energy

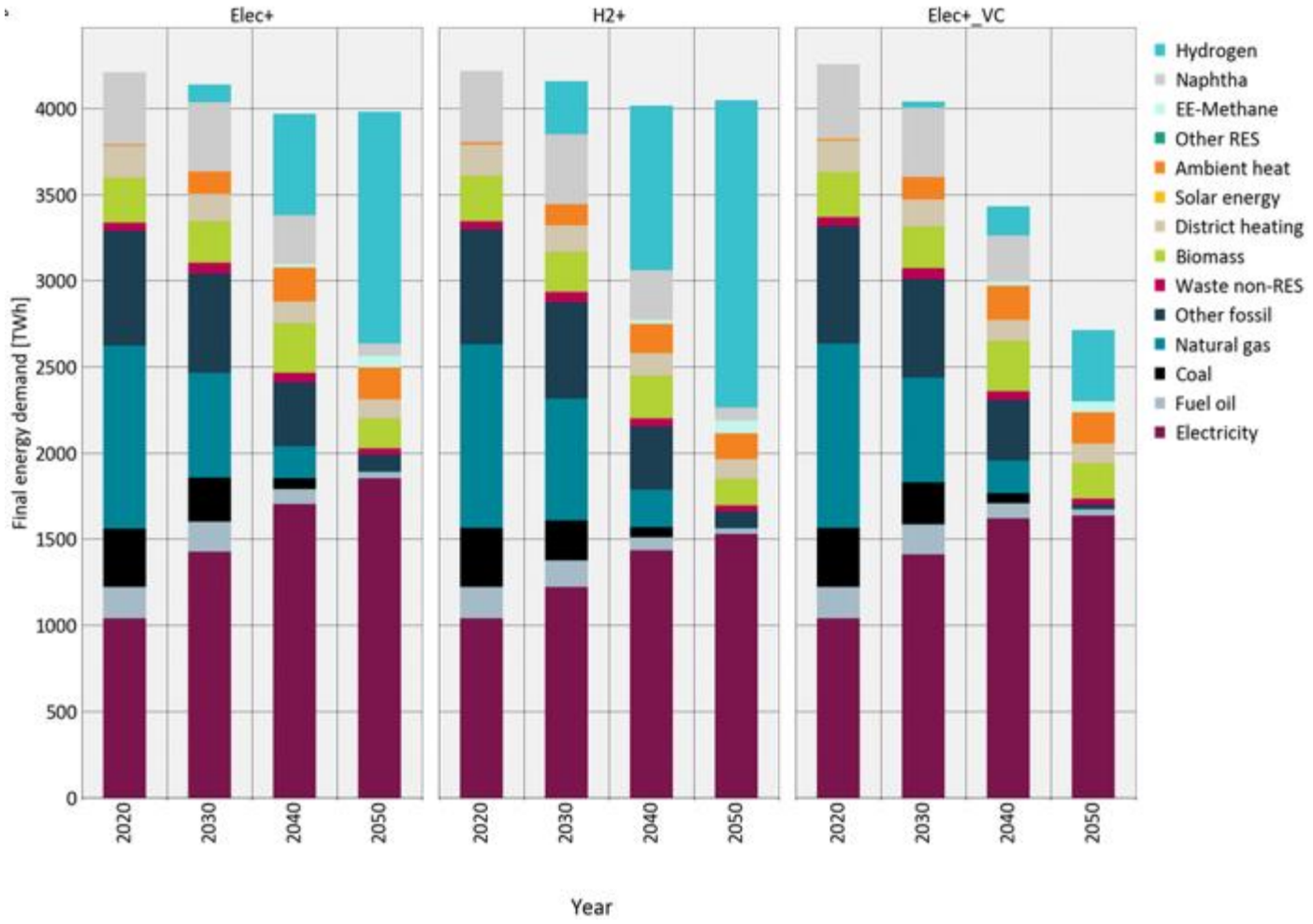
Results: Total industrial energy demand

Energy demand in 2050 is dominated by electricity and hydrogen (with some role for ambient heat, biomass, district heating, solar and geothermal)

Electricity increases from ~1000 TWh in 2020 to ~1855 TWh (Elec+) and ~1520 TWh (H2+)

Hydrogen increases to 1785 TWh (H2+) and 1340 TWh (Elec+)

The scenario Elec+_VC shows substantial imports of green interim products reducing direct H2 demand to ~416 TWh
(imports: 14 Mt ammonia, 20 Mt green ethylene and 34 Mt iron sponge)



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Energy demand for process heating shifts to electricity and hydrogen

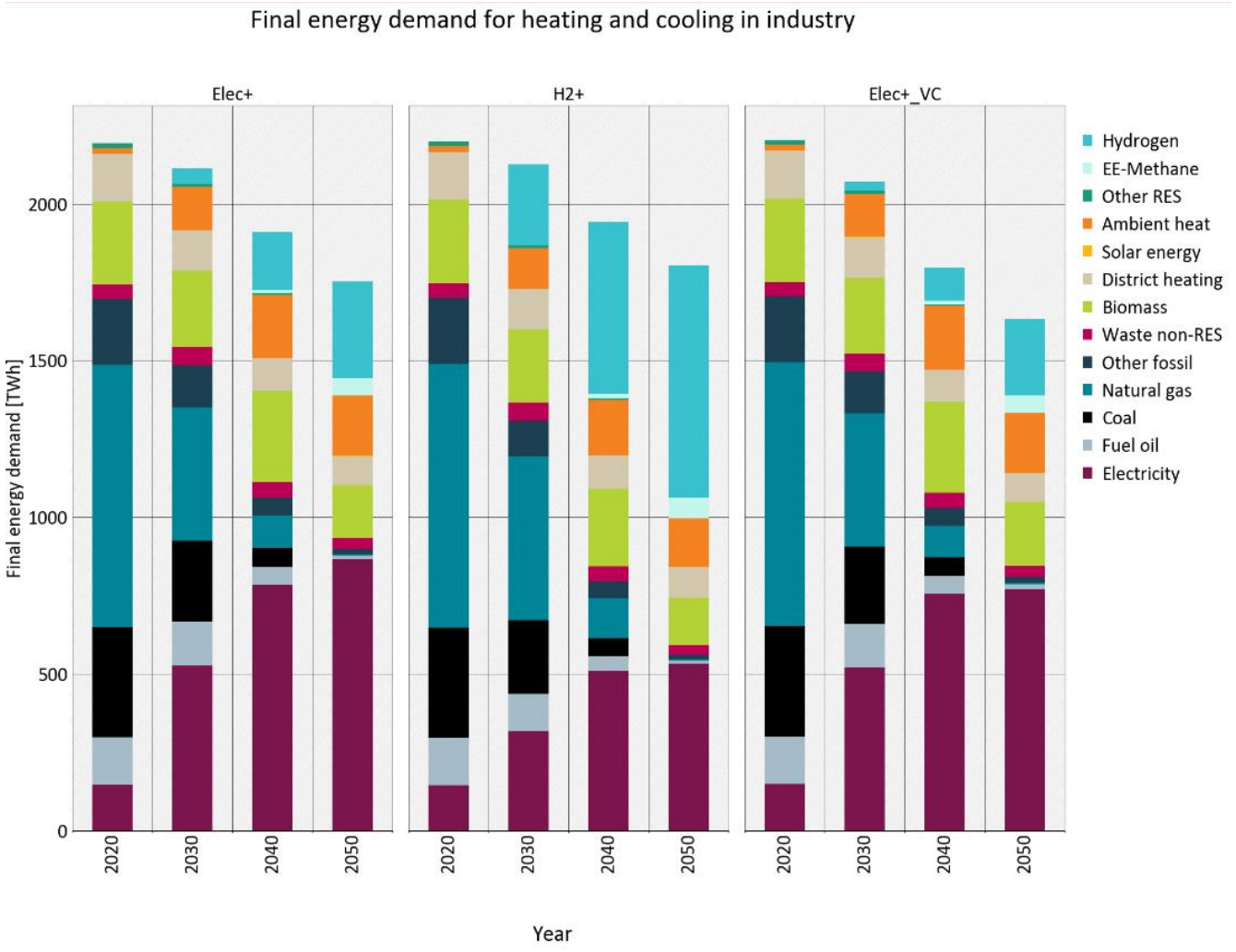
Results: Process heating

Process heating accounts for more than half of industrial energy demand

Status quo shows strong reliance on natural gas: 40%, 879 TWh in 2018

Strong increase in direct electrification in all scenarios: +720 TWh in Elec+, and +388 TWh in H2+

The remaining process heat is supplied by hydrogen, biomass, ambient/geothermal/solar heat and district heating



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Electrification of process heating overcompensates efficiency gains

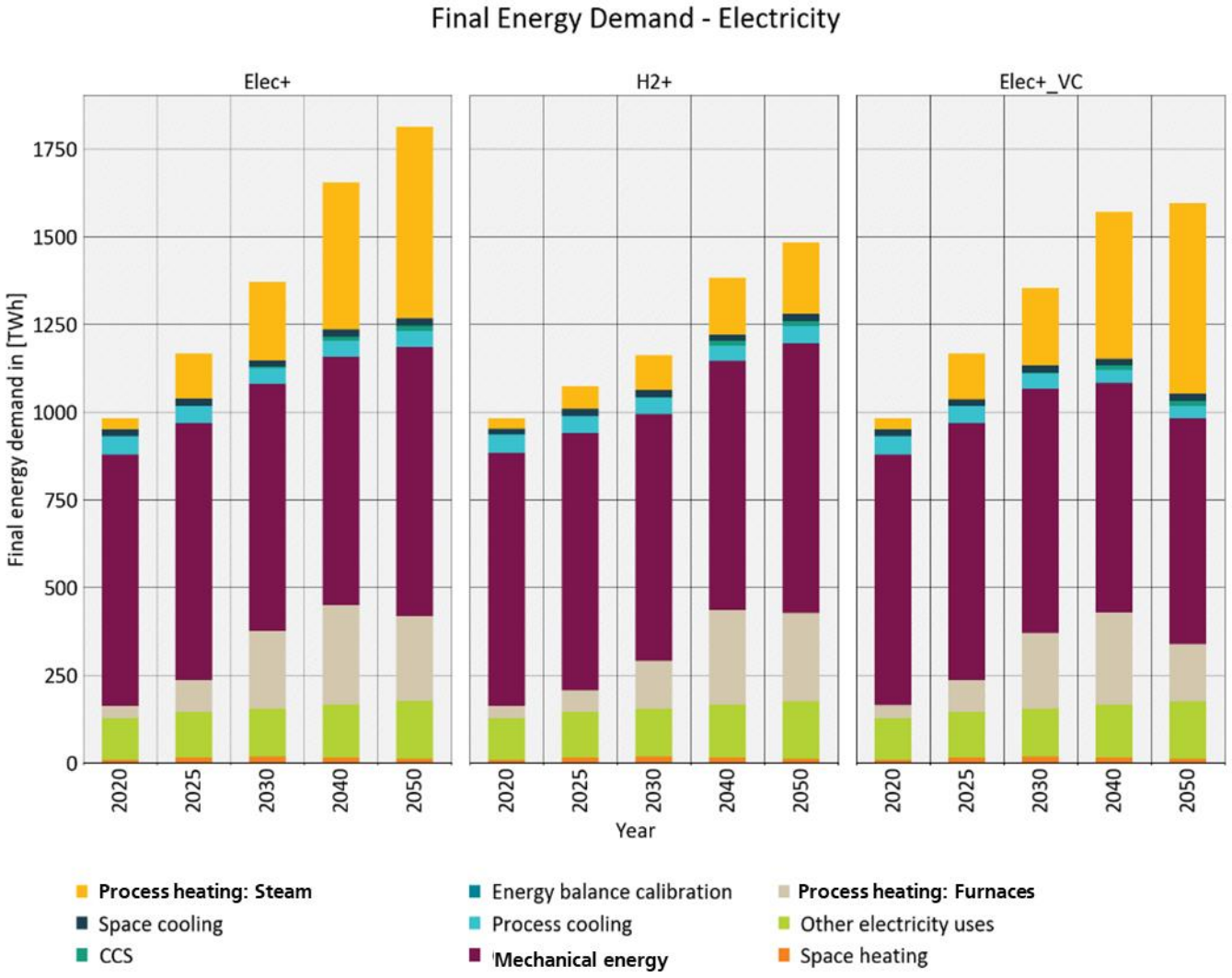
Results: Electricity demand by end-use

The figure shows only direct electricity use, possible electricity for production of secondary energy carriers like hydrogen is not included

Direct use of **electricity increases in all scenarios** by ~500 to ~700 TWh

Main driver is the **electrification of process heating**

Other **increasing trends from economic growth are compensated by efficiency gains** in cross-cutting technologies like electric motor systems



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Hydrogen demand is dominated by chemical industry in all scenarios

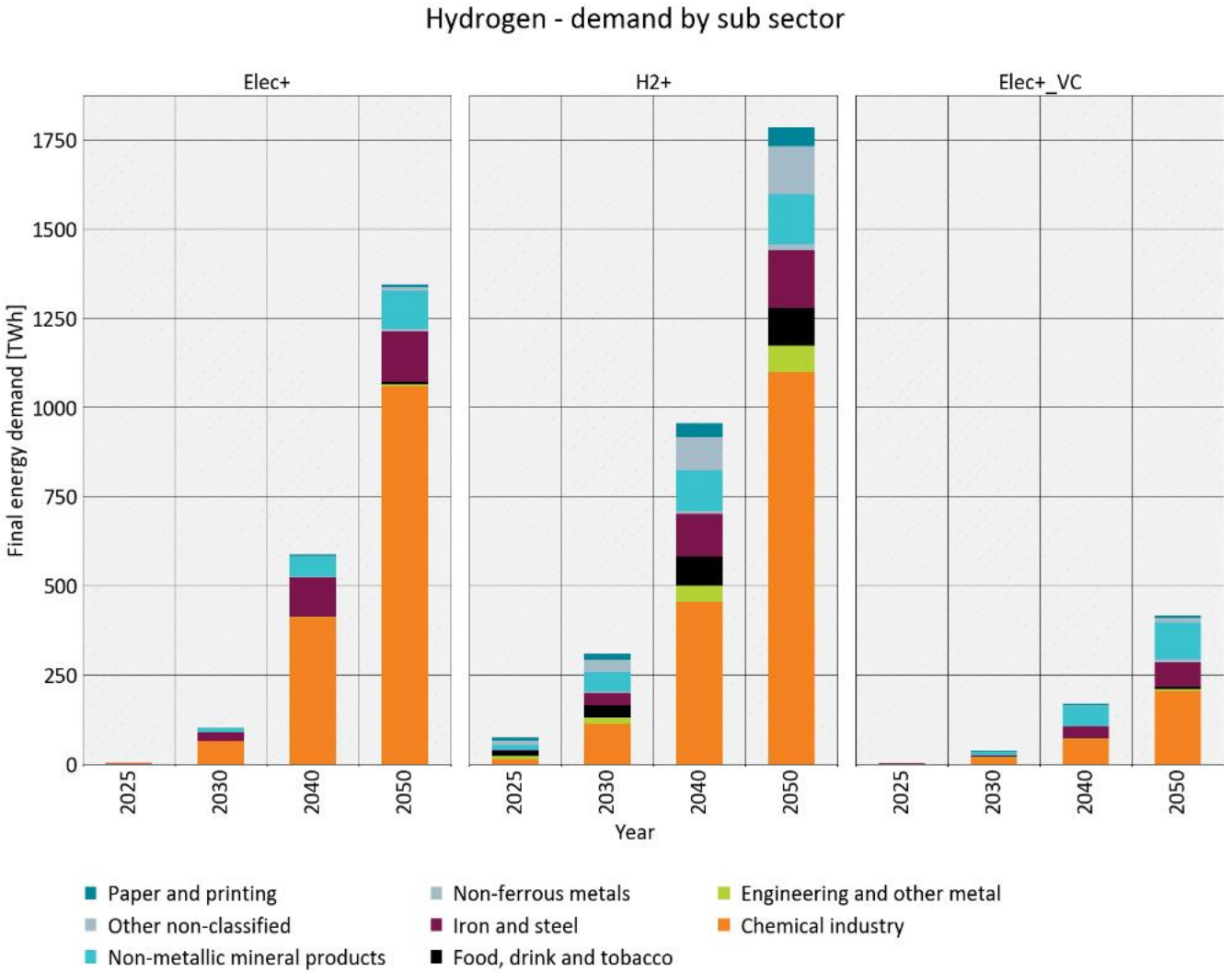
Results: Hydrogen

Hydrogen plays an important role in feedstock supply and for process heating in all scenarios ranging from ~450 to 1750 TWh in 2050

Largest demand sector is the chemical industry with up to ~1100 TWh for feedstock use

H2 demand for process heating adds about 250 to 650 TWh depending on take-up of direct electrification

Changing value chains with import of H2 derivates (ammonia, naphtha, iron sponge) can reduce H2 demand substantially



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Conversion of feedstock demand strong driver for hydrogen

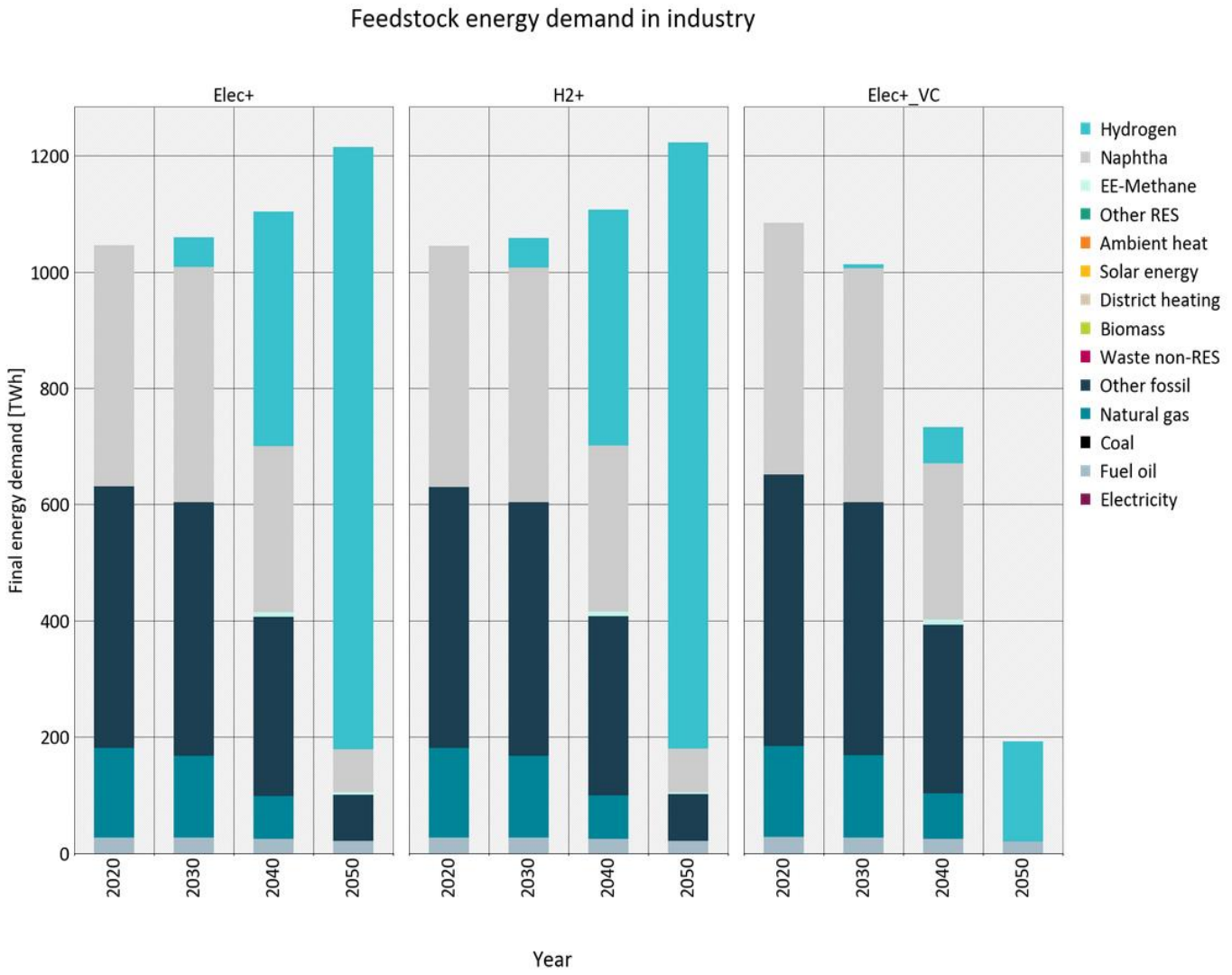
Results: energy demand for chem. feedstock

Huge feedstock demand for the production of olefins, aromatics, ammonia, and other chemical products

Today it is fully based on fossil fuels, mainly naphtha and natural gas

Results show a huge hydrogen demand of >1100 TWh by 2050 if methanol-to-olefins route is applied broadly

In case case H2 derivates like green ammonia or ethylene are imported directly, H2 demand can be substantially lower



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Energy Supply: key assumptions

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Total energy demand, all sectors, 2050

24% reduction in TED by 2050 compared to 2019 driven by efficiency gains in the building sector and the diffusion of energy-efficient electric vehicles in transport

Hydrogen is emerging as a key energy carrier it could potentially make up 24-32% of final energy demand.

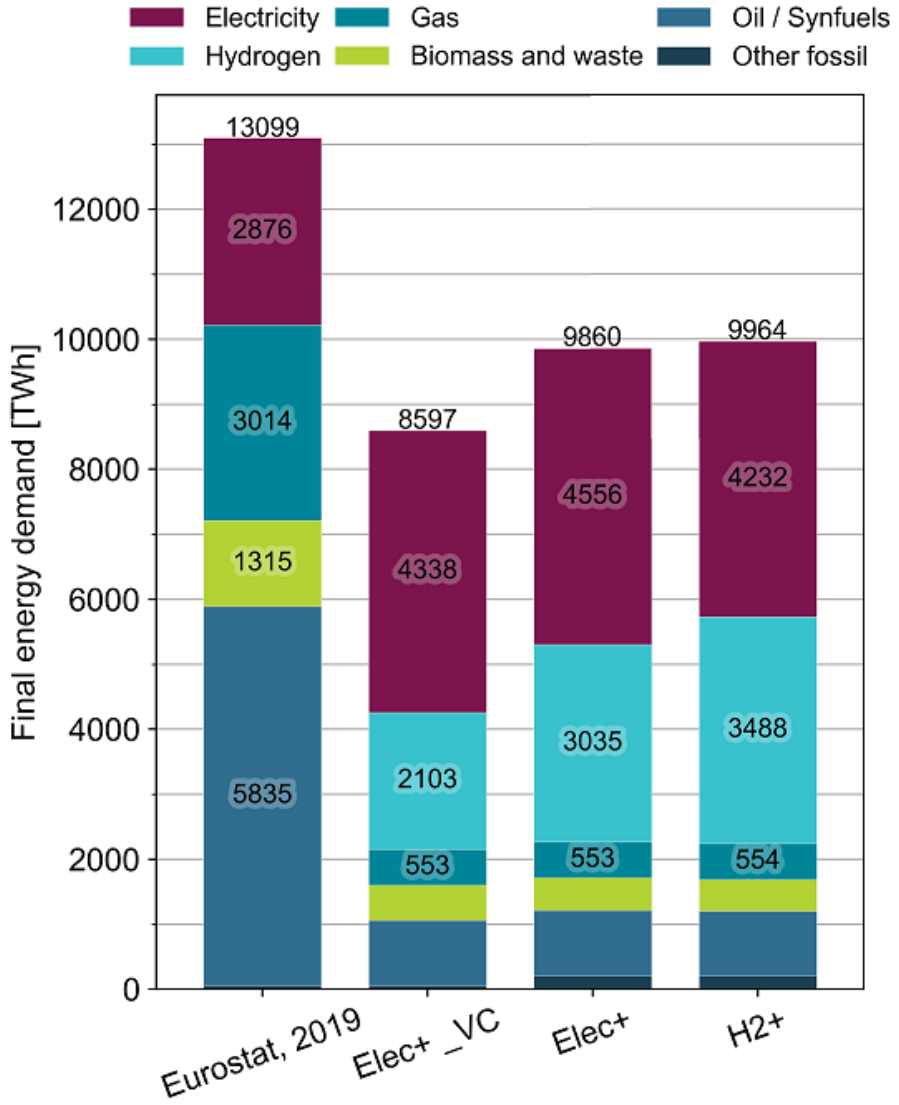
H2+ compared to Elec+/ Elec+_VC:

- ↑450 / 1385 TWh hydrogen for process heating
- ↓325 / 106 TWh electricity for process heating

All supply-side data is EU27+UK+NO+CH, if not stated otherwise.

Industry (including feedstocks/non-energy use)

FORECAST model provides the demand for industry and the demand from other sectors is taken from the PRIMES Mix-H2 Scenario



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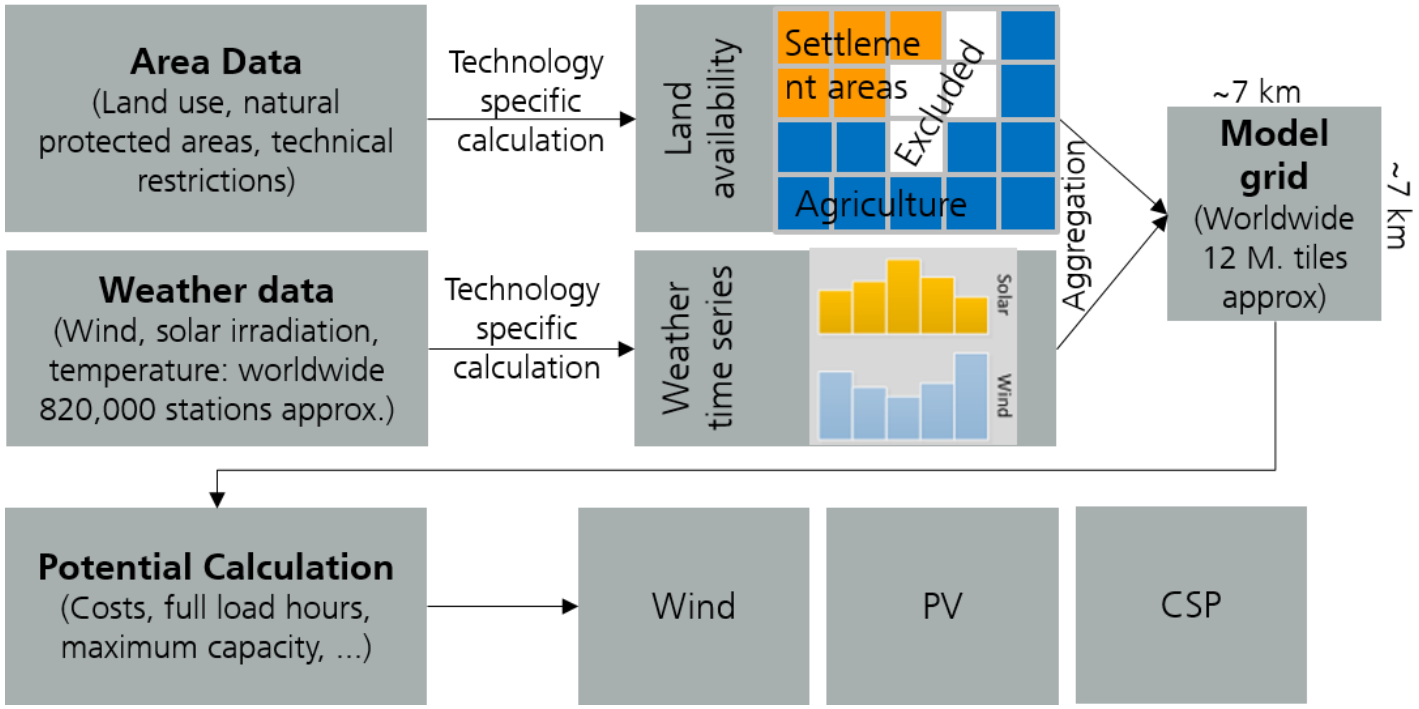
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Methodic calculation of wind and PV generation potentials

The methodology has:

- High geographic resolution (hectar-level-6.5x6.5km2)
- Technology assumptions for 2050 (costs, land-use restrictions,..)
- Conservative assumptions for PV calculation in 2050
  - CAPEX 500 €/kW
  - Lifetime:20 years
  - Efficiency 19%
  - High effect of temperature in efficiency
- Three weather years (2010, ’12, ’15)

-> See data report



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Assumptions: Land use factors by type of land cover

Land use/availability

- Input data: CORINE land cover (250 m resolution
- Higher factors for wind as they permit mixed use better

Installable capacity

wind: onshore & offshore: 9 x 5 x rotor diameter² / 90%

PV: module area x overhead factor (3.35 for utility-scale)

CSP: solar field area x overhead factor (5)

Type of land use	Utility scale PV	CSP	Wind Onshore
Barren land	16%	12%	20%
Cropland	2%	2%	16%
Forest	0%	0%	12%
Grassland	2%	2%	20%
Savannah	2%	12%	20%
Shrubland	2%	12%	20%
Snow and ice	4%	0%	12%
Urban	0%	0%	0%
Water	0%	0%	0%
Wetlands	0%	0%	0%

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Wind and solar energy cost-potential curve, EU 27 + UK

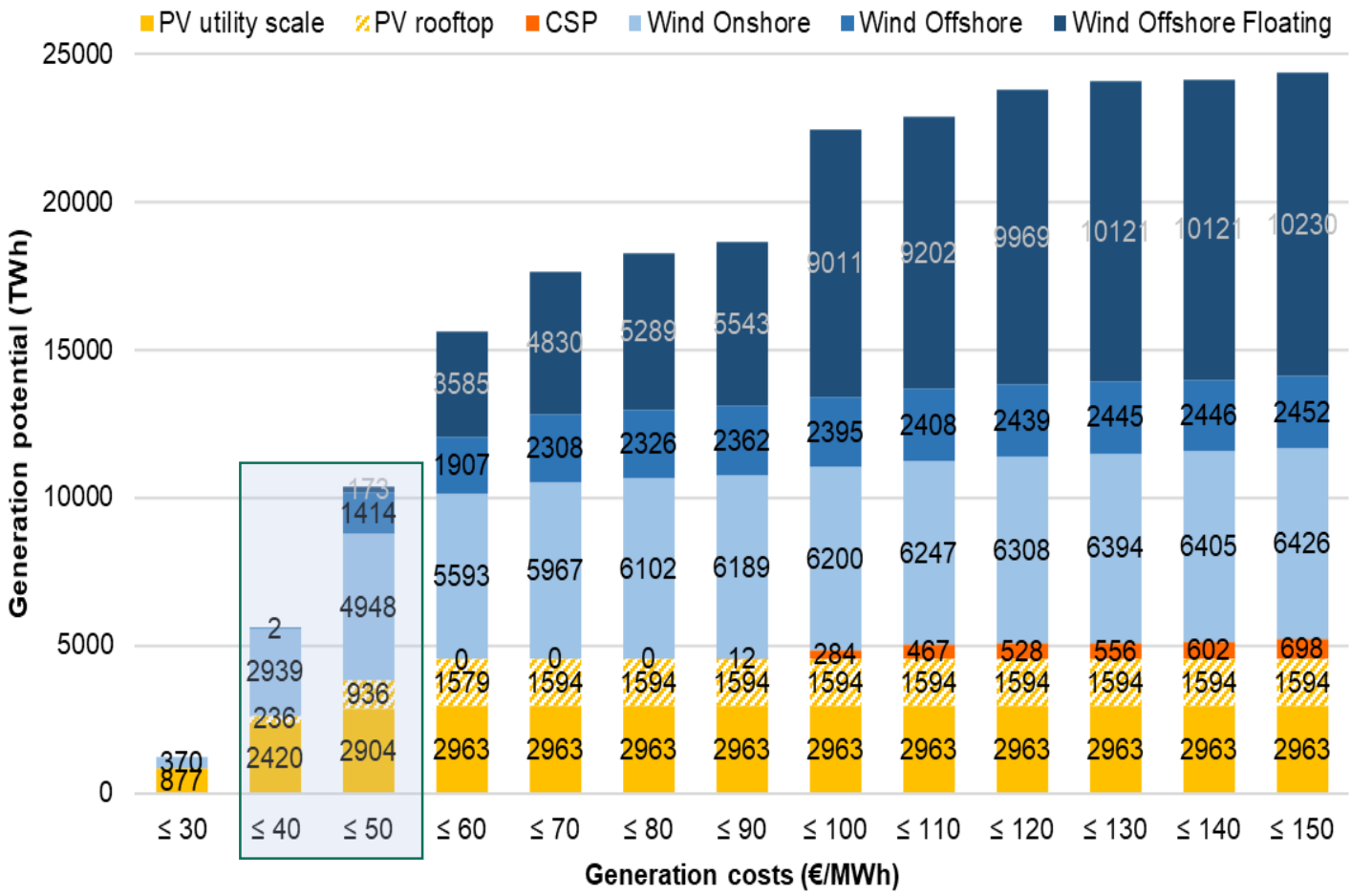
From METIS 3 data collection

Dedicated METIS assessment of RES potentials shows:

Europe has a significant amount of renewable energy. with technical potential of 10,000 TWh below 50€ / MWh, primarily onshore wind and utility-scale PV

The asessment has:

- High regional resolution (hectar-level)
- Technology assumptions for 2050 (costs, land-use restrictions,..)
- Three weather years (2010, ’12, ’15)



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Energy Supply: Metis results

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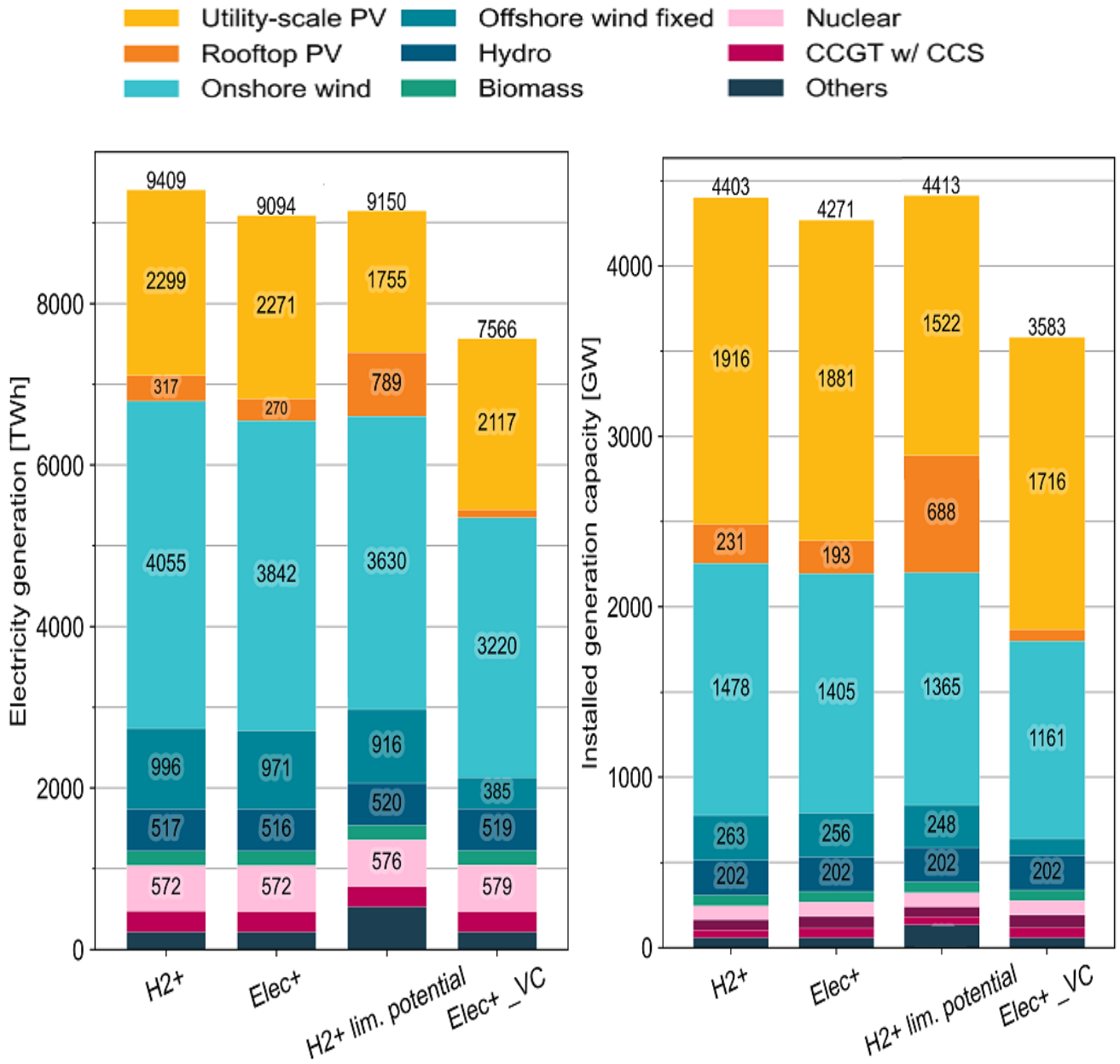
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90% renewable electricity supply in 2050

Deployment of RES follows the least-cost approach

- Renewable sources contribute to ~90 % of overall electricity production, thereof 82% are wind and solar
- Residual load is supplied by nuclear, CCGT w/CCS, biomass and storage
- Differences between Elec+ and H2+
  - 400 TWh difference is primarily due to the lower efficiency in the hydrogen energy conversion chain,
  - The increase is mainly supplied by wind onshore (+200 TWh)
- **Compare 2023: ~2400 TWh electricity gen.**



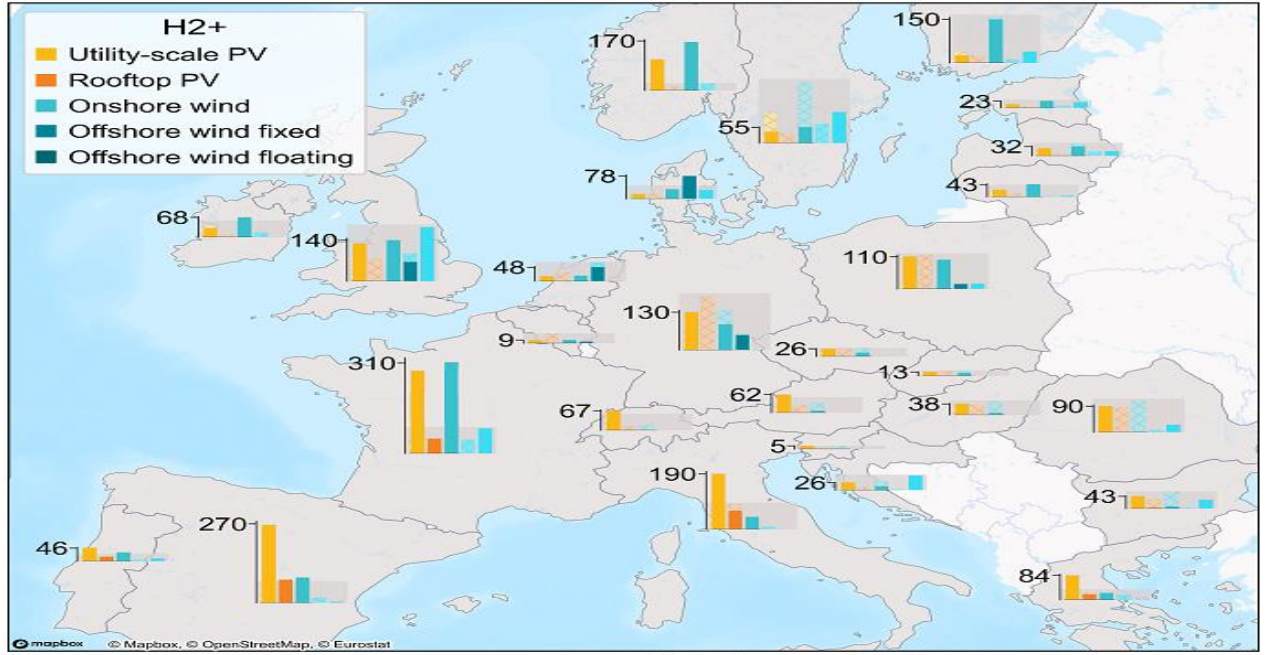
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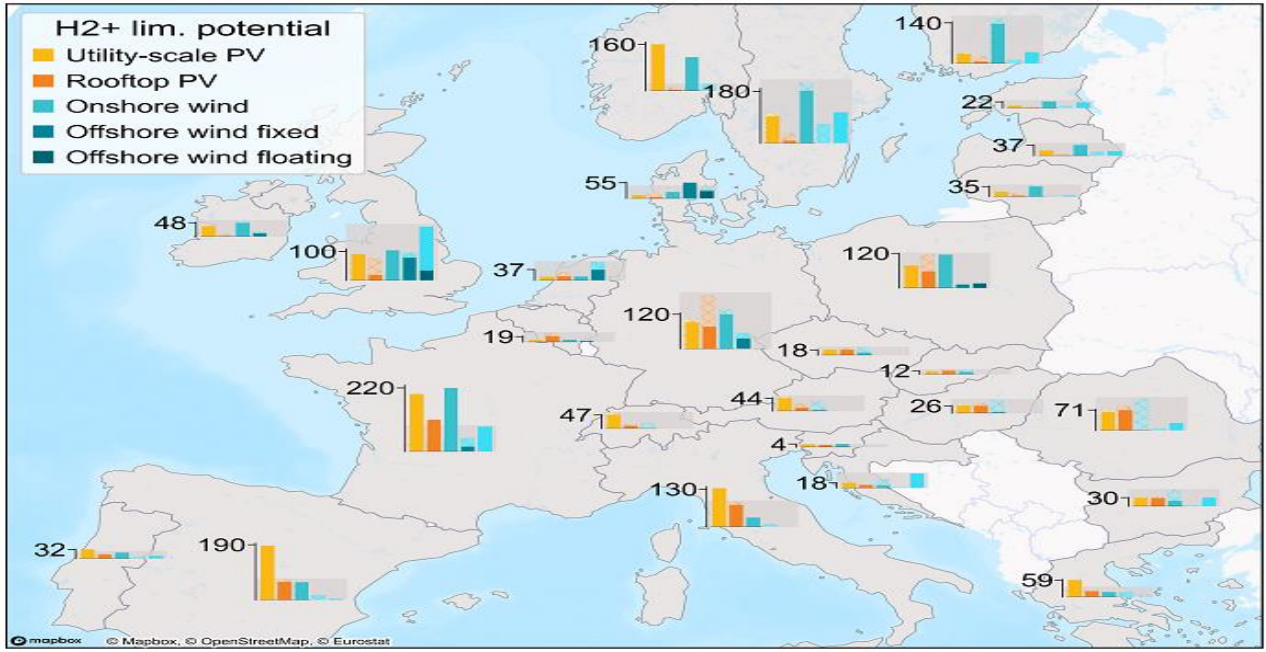
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Utility-scale PV is the most widely installed technology with about 44% of installed capacity

Supplying all European energy demand domestically is possible in an optimal scenario
It requires ambitious RES deployment:

- Prioritizing cost-effectiveness and ensuring efficient utilisation results in **70% utilisation of the utility-scale PV potential**
- **Onshore and offshore wind** is strongly deployed in all North-Western countries with good wind potential (1000GW)
- **Rooftop PV** is only used in southern Europe with the highest solar radiation





** Hatched bars show each countries' potential for the respective RES technologies

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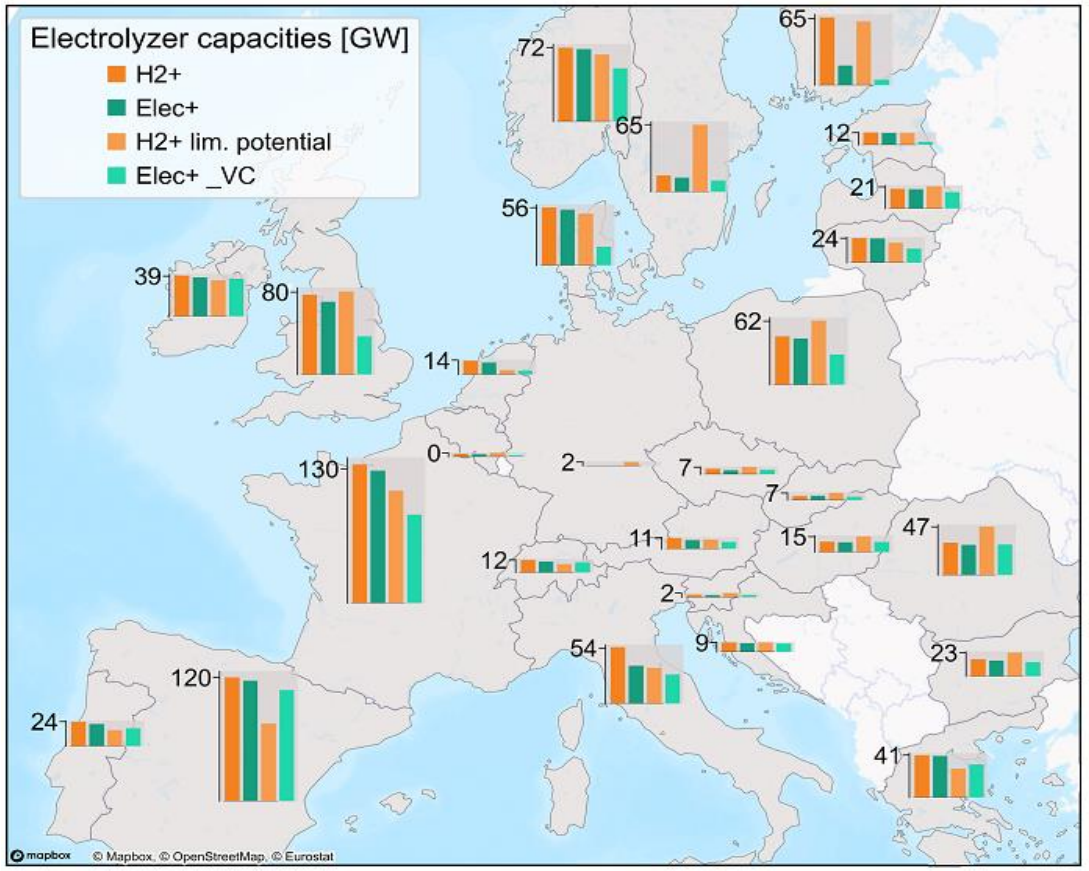
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Hydrogen production is allocated close to large RES potentials

The entire European hydrogen demand is produced domestically, requiring significant amounts of renewable electricity, a total of 810 GW and 915 GW of electrolysis capacity installed in the Elec+ and H2+ scenarios

From a cost-optimization perspective, long-distance transport of hydrogen to central demand centers is more efficient than local production

- Countries with large chemical and steel industry import most of their hydrogen demand, see Germany, Netherlands and Belgium
- Hydrogen production is allocated in countries with high RES potentials and exported, see France, Spain, UK, Norway, Denmark, Finland, Baltics



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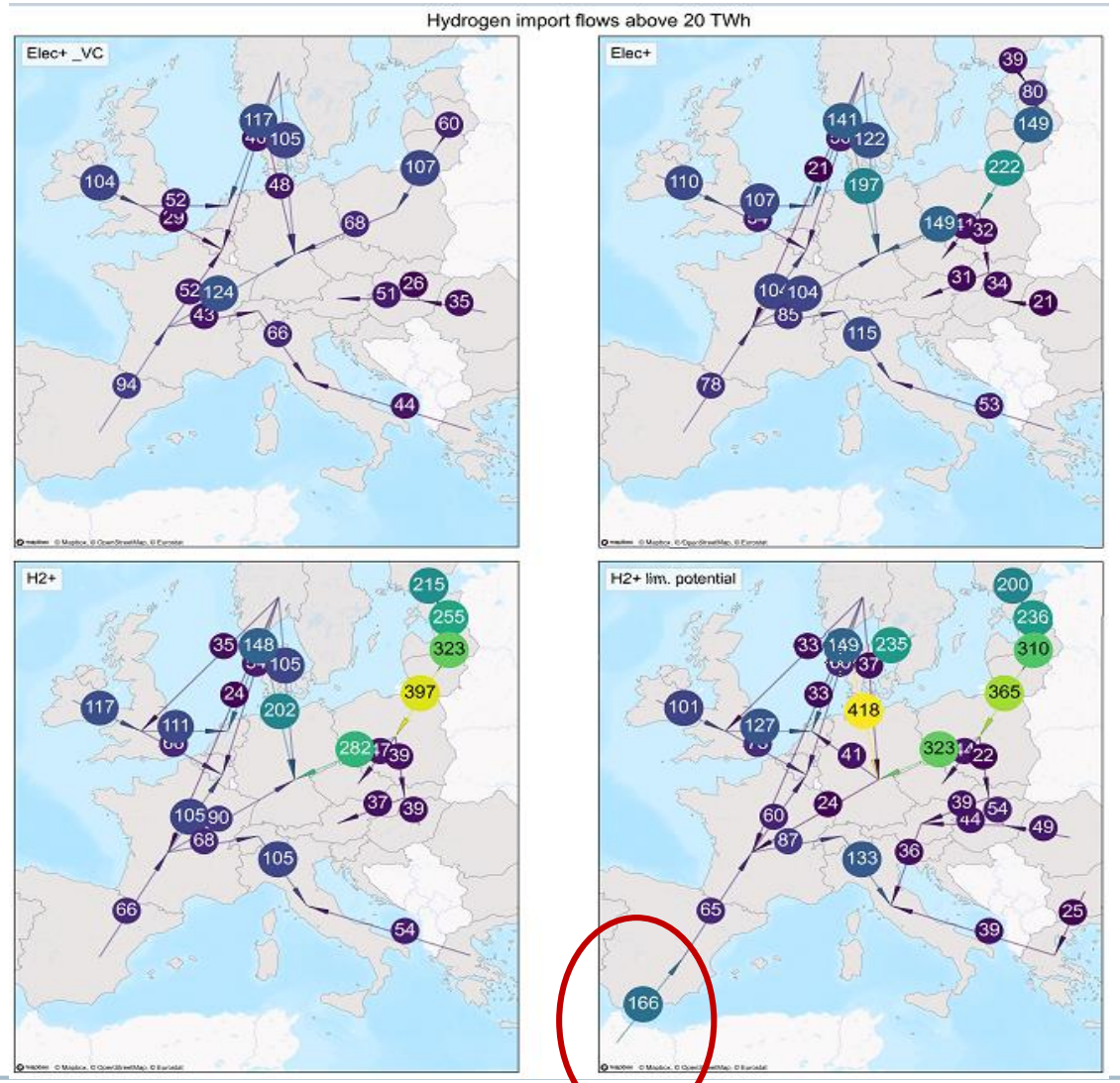
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A pan-European hydrogen network supplies a low-carbon industry in central Europe

The pan-European hydrogen network connects demand centers in central Europe with large, low-cost potentials for renewable generation

- Important transport corridors are: Baltics, Scandinavia, UK, Iberian/France
- Also the scenario Elec+ shows a high demand for pan-European hydrogen transport
- The additional H2 demand in the scenario H2+ is mainly supplied via Baltics
- In H2+ Limited potentials the higher cost for domestic hydrogen production make non-EU imports cost-competitive
- First imports can be seen: **166 TWh of hydrogen are imported from Morocco**



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Conclusions

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Conclusions

1. **Electricity becomes the most important energy carrier and the demand for it grows.** 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.

2. **Hydrogen** and/or derivatives are required for low-carbon production in **chemicals and steel up to 1800 TWh** if the **chemical value chain is not offshored** (hydrogen demand from industry drops to 416 TWh)

3. **Domestic hydrogen production** is available at a lower cost than assumed H2 import costs from non-European countries; **only when RES deployment is sub-optimal/constrained,** imports of hydrogen become cost-competitive.

4. Results show a system based on cost optimization, from a **technical perspective,** renewable energy sources have the potential **to meet all of Europe's energy demand at competitive costs**. However, this will require a massive deployment of **Solar and Wind and** a **pan-European hydrogen network** connecting the **high-demand centers** with **regions with high low-cost potentials** for renewable energy generation.

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Thank you for your attention!

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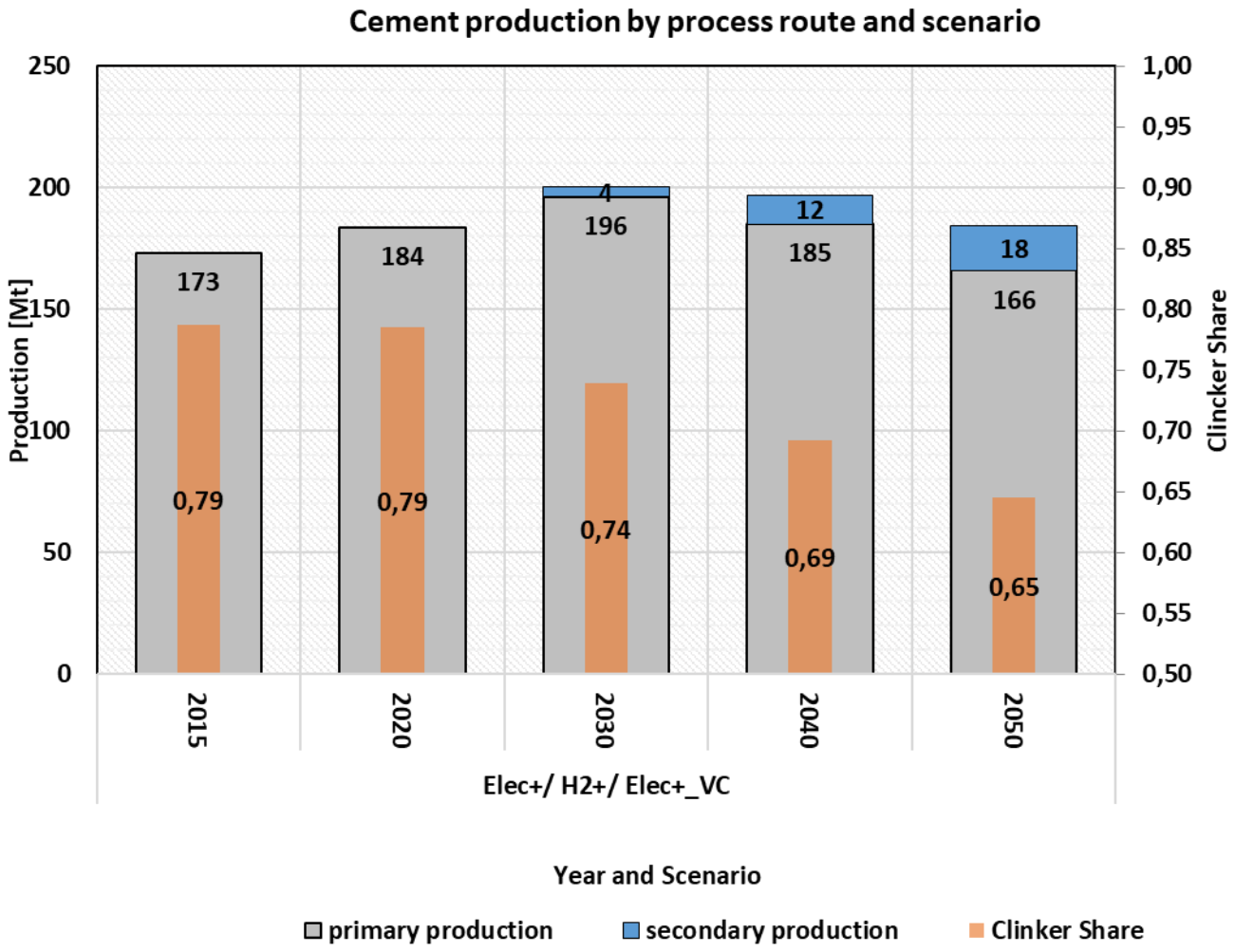
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What does the ambition in wind and PV expansion mean compared to the status-quo?

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EU hydrogen production can achieve lower costs than imports

Marginal costs of domestic production of H2 are slightly below the least cost import options if European system develops cost-optimal

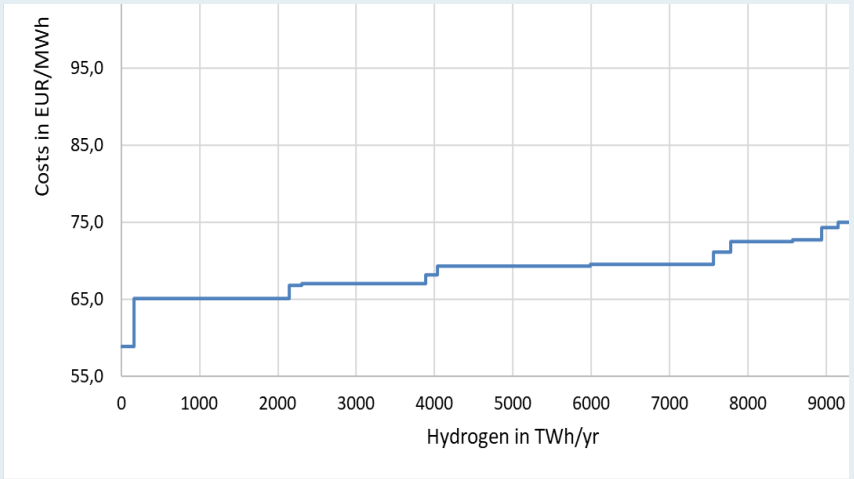
In case of less optimal RES deployment imports become cost competitive (H2+_LimPot)

While only small quantities of H2 are imported, the cost-potential curve shows huge quantities at similar costs

Some limitations apply:

- **Assessment considers system costs (different to possible future prices)**
- **No limitations in hydrogen transport infrastructure**
- **Alternative imports of H2 derivates like ammonia not considered**

Cost curve for hydrogen from MENA Region, 2050 (7% WACC)



Benjamin Lux, Johanna Gegenheimer, Katja Franke, Frank Sensfuß, Benjamin Pfluger, Supply curves of electricity-based gaseous fuels in the MENA region, Computers & Industrial Engineering, Volume 162, 2021, https://doi.org/10.1016/j.cie.2021.107647.

Marginal cost of energy carriers [€ / MWh] (Demand weighted average)

	Elec+	H2+	H2+_LimPot
Hydrogen	59	61	68
Electricity	48	46	

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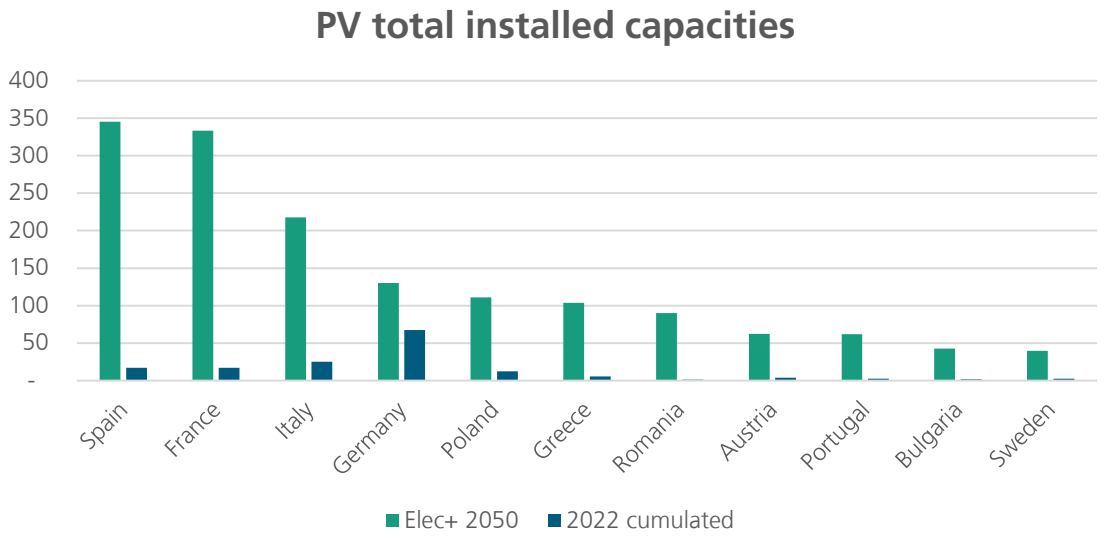
PV: Comparing results to status-quo

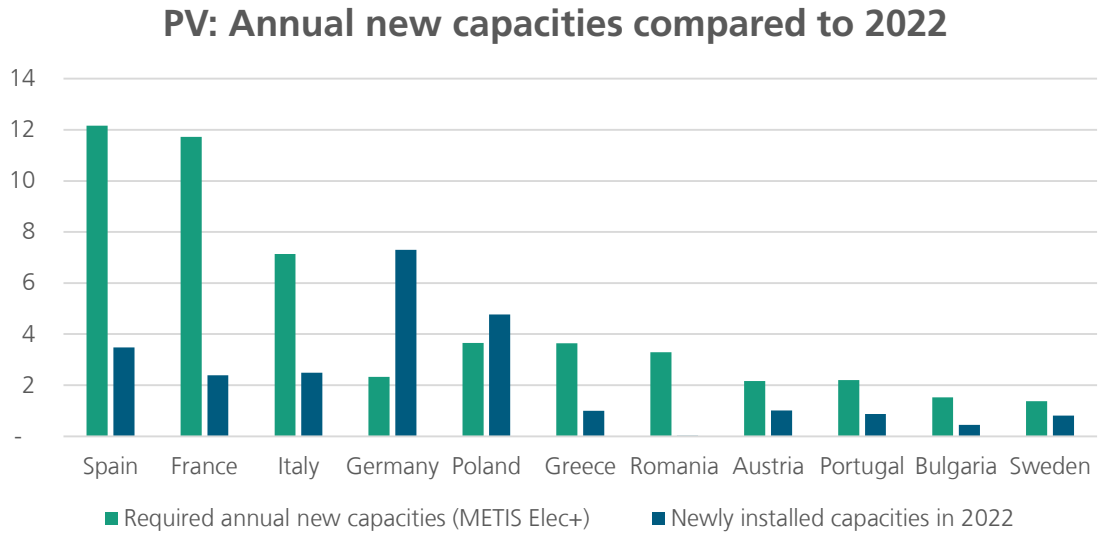
EU27 installed capacities:

- **METIS Elec+: 3000 GW PV capacity by 2050**
- **Status-Quo in 2022: 195 GW (7 % of required 2050 target)**

EU27 annual new capacity:

- **Required annual new capacity: 100 GW**
- **Total new capacity in 2022: 33 GW (32% of required new installations)**





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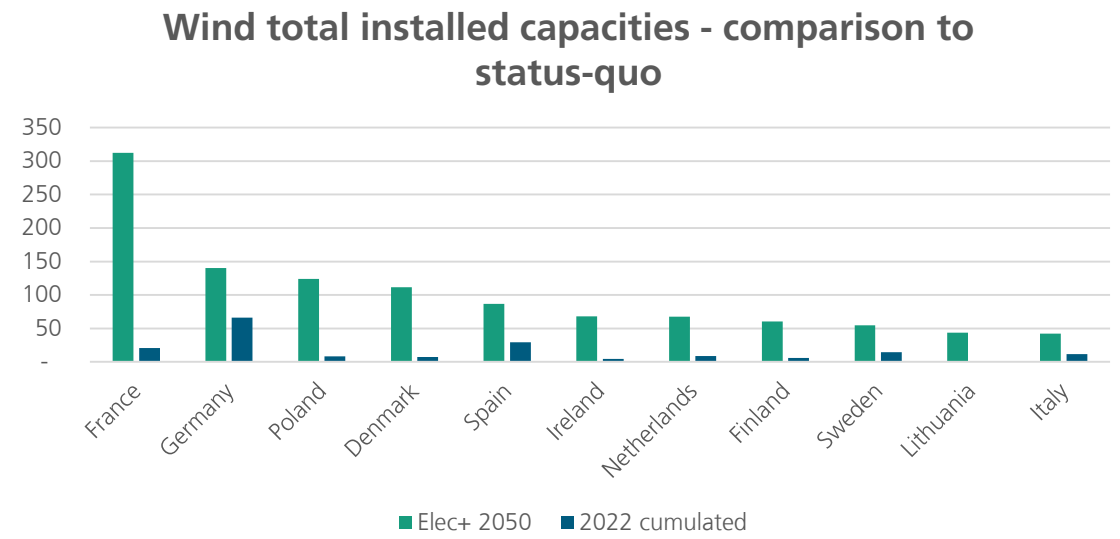
Wind: Comparing results to status-quo

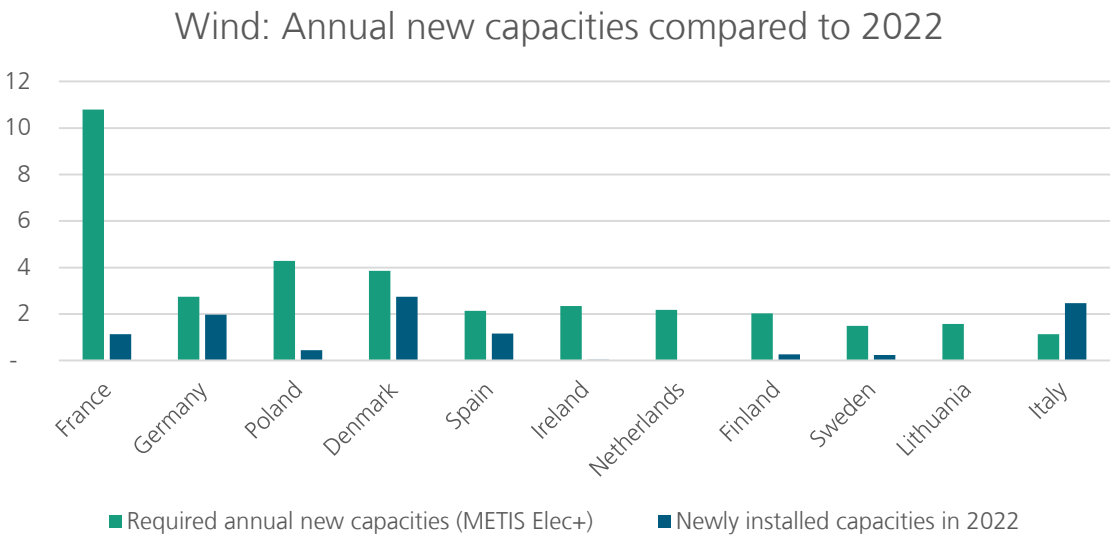
EU27 installed capacities:

- **METIS Elec+: 1,300 GW PV capacity by 2050**
- **Status-Quo in 2022: 200 GW (16% of required 2050 target)**

EU27 annual new capacity:

- **Required annual new capacity: 41 GW**
- **Total new capacity in 2022: 15 GW (37% of required new installations)**





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