Pathways to 2050: the role of nuclear in a low-carbon Europe

Final report

15 October 2024

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1.

Study context and objectives

Context and objectives of the *nucleareurope 2050 Pathways study*

In the context of the latest EU policy ambition towards decarbonisation and Net Zero, and accounting for the latest market and technology developments, nucleareurope has mandated Compass Lexecon to update the *2050 Pathways study* undertaken with *nucleareurope* back in 2020 and 2018:

- The *2050 Pathways study* analyses the potential contribution of nuclear generation towards the decarbonisation of the European electricity system in different scenarios regarding nuclear installed capacity, with a specific focus on the timing and extent of nuclear plants phase-out, lifetime extensions, and new build.
- The different scenarios regarding nuclear installed capacity are simulated in Compass Lexecon pan-European power market dispatch model from which several relevant financial and physical indicators are derived to assess the potential contribution of nuclear generation.

This report updates the modelling underpinning previous editions of the *2050 Pathways study* and analyses the contribution of nuclear generation towards a climate neutral EU economy by considering specifically three issues :

1. **The power system -** as per previous studies - accounting for the accelerated decarbonisation objectives and updated cost and commodities assumptions.
2. **The broader energy system**, by assessing the additional benefits of producing more European green hydrogen vs imports.
3. **The industrial heat sector**, by assessing the addressable market in the industrial heat sector for SMRs.

The contribution of nuclear generation towards a low-carbon European economy is assessed against three policy objectives

Policy objectives

Decarbonisation and sustainability

Security of supply

Affordability and competitiveness

Key research questions

- Can an EU scenario with a fully decarbonized electricity mix be **credible, secure and cost efficient** without a significant share of nuclear?
- What is the role that nuclear can play in an EU decarbonisation scenario with **growing power demand driven by strong electrification** of the economy?
- How to manage nuclear plant closures, life extensions and new build in different countries to **avoid locking in inefficient fossil fuel technologies and emissions** in transition to a decarbonised power sector?

This study aims at **delivering fact-based evidence in response to these key questions** by analysing the contribution of the European nuclear sector across three different scenarios to achieving European energy policy objectives of security of supply, decarbonisation and sustainability, and affordability / competitiveness.

The study compares 3 scenarios of nuclear development in the EU that vary with the installed capacity between 2030 and 2050

#100GW
100 GW Nuclear in 2050

Reflective of the Business-as-usual view on nuclear capacity development

#150GW
150 GW Nuclear in 2050

Reflective of more ambitious policies and targets to develop nuclear capacity in the EU

#200GW
200 GW Nuclear in 2050

Reflective of a change in paradigm, giving nuclear a central place in the transition to Net-Zero

Common assumptions

Power demand:	TYNDP 24 Scenario DE[1]
Commodity prices:	Based on IEA WEO23 AP scenario and CL modelling
Technology costs:	Based on the most recent "Technology Pathways (European Commission, 2024)

Differentiated assumptions

Renewable installed capacity	- 2030 capacity based on TYNDP 2024 projections - For later years: Optimised based on least cost & potential
Thermal and flexible installed capacity	Optimised to ensure security of supply
H2 electrolysers demand	Based on TYNDP projections of European H2 production [2]

Note: [1] DE: "Distributed Energy" scenario [2] Different in the "energy system" approach, #150GW and #200GW scenarios, to follow the variations in available low carbon generation

2.

Executive Summary

The study assesses the potential contribution of additional nuclear power to decarbonise the EU economy and reach net zero by 2050

Starting from a Business-as-usual view on nuclear development (*#100GW scenario* of 100 GW nuclear capacity in 2050), the study analyses in the *#150GW scenario* and *#200GW scenario* the impact of an **additional capacity of 50 GW of nuclear capacity in the EU by 2050 (respectively 100 GW).**

The modelling of the three scenarios shows that :

- **Nuclear power generation can contribute to system flexibility and thus complement RES, flexible resources and storage development to reach Net Zero by 2050.** Compared to the #100GW scenario over the period 2030-50, 50 GW (resp. 100 GW) of additional nuclear capacity could provide flexibility equivalent to c100 GW in storage capacity (resp. c170 GW).

- **By substituting thermal generation, increased nuclear generation contributes to reducing gas imports and power system carbon emissions.** Compared to the #100GW scenario over the period 2030-50, 50 GW (resp. 100 GW) of additional nuclear capacity could **:**
  - ➢ Save c180 bcm of gas consumption, i.e 37% reduction (resp. c220 bcm , i.e 44% reduction)
  - ➢ Reduce CO2 emissions by c430 Mt i.e. 35% reduction (resp. c500 MtCO2, i.e. 41% reduction)

- **Additional nuclear power generation could mitigate the total power system costs associated with the transition to net zero, in particular network and balancing costs.** Compared to the #100GW scenario over the period 2030-50, 50 GW (resp. 100 GW) of additional nuclear capacity could lead to a system cost benefit of €310bn (respectively €450bn).

The study also assesses the benefits for the broader energy system of additional nuclear generation in reaching climate neutrality by 2050

Our modelling includes analyses taking an integrated approach in the broader energy system to assess the contribution of nuclear generation in reducing carbon free H2 imports and helping decarbonise heat supply in the industrial sector.

Our key findings are as follows:

Additional nuclear capacity in the power system could help reducing carbon free Hydrogen imports by 2050

- Carbon free Hydrogen will play an important role in the decarbonisation of the EU energy system.
- Domestic of Carbon free Hydrogen is projected to increase across the EU, but significant imports are likely to be needed to meet demand.
- Compared to the #100GW scenario in 2050, 50GW (resp. 100GW) of additional nuclear capacity could reduce carbon free H2 imports by 125 Mt H2 over 2030-2050 i.e. 33% reduction (230 Mt H2 over 2030-2050 i.e. 61% reduction).
- This could lead to an energy system cost benefit of €390bn over 2030-2050 (resp. €580bn).

Nuclear power could contribute to decarbonise “medium to high temperature”* industrial heat by 2050

- Industrial heat is a key energy component of the energy system that needs to be decarbonised by 2050.
- Within the heat sector, Small Modular Nuclear Reactors (SMRs) could provide decarbonised heat for medium to high temperature industrial applications. Large nuclear plants could also provide heat for the same applications, as it is already the case in some industrial clusters.
- The corresponding industries are projected to require c877 TWh of additional net-zero heat by 2050. This would equate to c133GW of installed nuclear thermal capacity.

*Note: *Medium to high temperature industrial heat refers to temperature from 200C to 1000C*

3.

Scenario definition and modelling framework

The study compares 3 scenarios of nuclear development in the EU that vary with the installed capacity between 2030 and 2050

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Note: [1] Different in the “energy system” approach, #150GW and #200GW scenarios, to follow the variations in available low carbon generation

nucleareurope scenarios differ by the amount of nuclear capacity extended (LTO) as well as new large scale and SMR projects

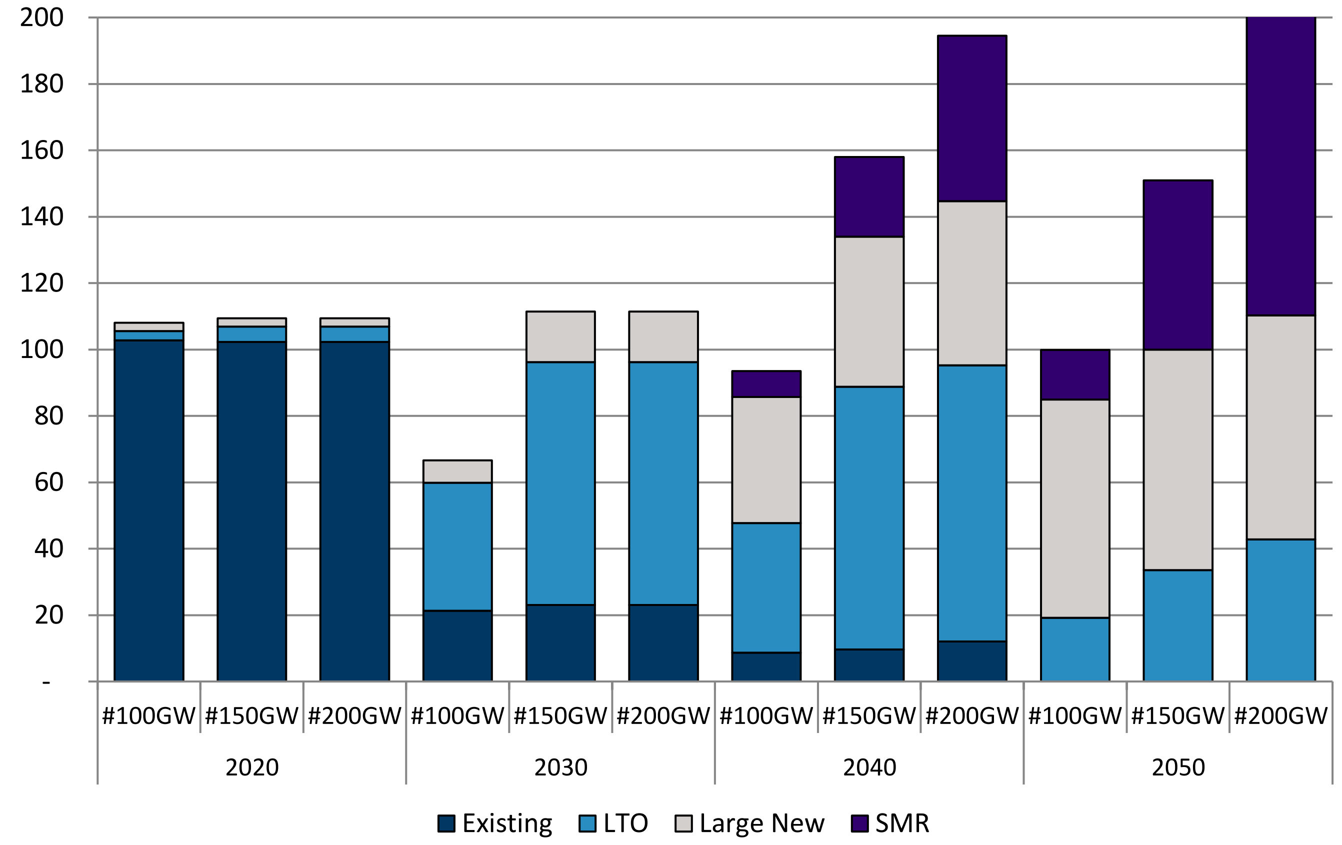
By 2030, most of the difference in nuclear capacity projections comes from different views on extensions

- By 2030, the #100GW scenario projects some important volume of nuclear plant retirement, including 25 GW in France and around 7 GW in both Germany and Spain. 4 GW of new build nuclear is projected to be commissioned.
- In the #150GW and #200GW scenario, only 9 GW is projected to be retired by 2030, with the rest of the capacity being extended. Around 13 GW of new build capacity is projected to be commissioned by then.

By 2050 the main difference between the scenarios comes from the vision on SMR development

- By 2050, nucleareurope assumes 200 GW of nuclear capacity in the most ambitious scenario. This assumes a development of more than 90 GW of SMR capacity
- The development of SMR capacity is less ambitious in the other scenarios, with 15 GW assumed in the #100GW scenario and 51 GW in the #150GW scenario

EU Nuclear installed capacity in the different scenarios - 2020 to 2050 (GW)



 Source: nucleareurope, CL Energy Analysis

Power demand is projected to increase and become more flexible (based on ENTSOE TYNDP DE scenario) due to the electrification of end uses

The European decarbonisation targets are expected to be met with increased electrification of the most carbon-intensive sectors of the economy, typically : (i) Transport; (ii) Heating and Cooling; (iii) Industry; (iv) Data centres.

- Demand evolution is characterised with ambitious electrification targets, particularly in transport, heating and industrial sectors, in order to meet the decarbonisation objectives

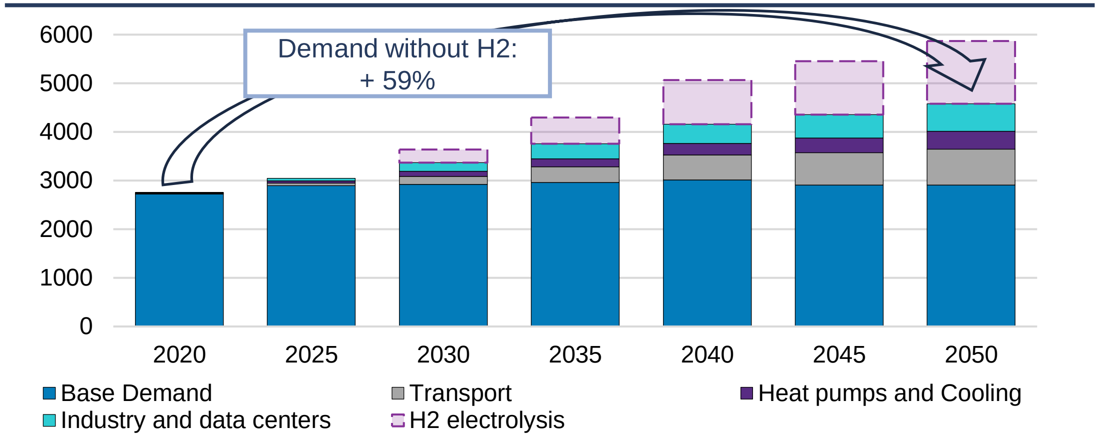
The production of H_2 through electrolysis is projected to significantly increase the energy demand in both scenarios

- Demand associated with H2 production is one the key uncertainty to future electricity demand

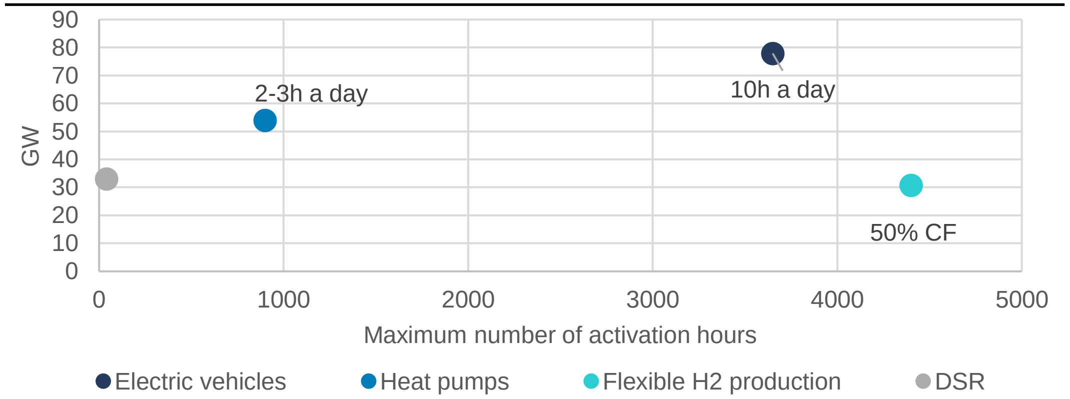
The projected penetration of renewables, and climate targets, leads to an important need of demand flexibility in the system

- Demand flexibility is needed to limit the use of carbon-intensive generation during periods of low renewable power generation.
- Both scenarios are characterised with an important penetration of renewable energy, calling for an important growth in flexible demand.

Aggregated power demand, EU27 - 2020-2050 [TWh]



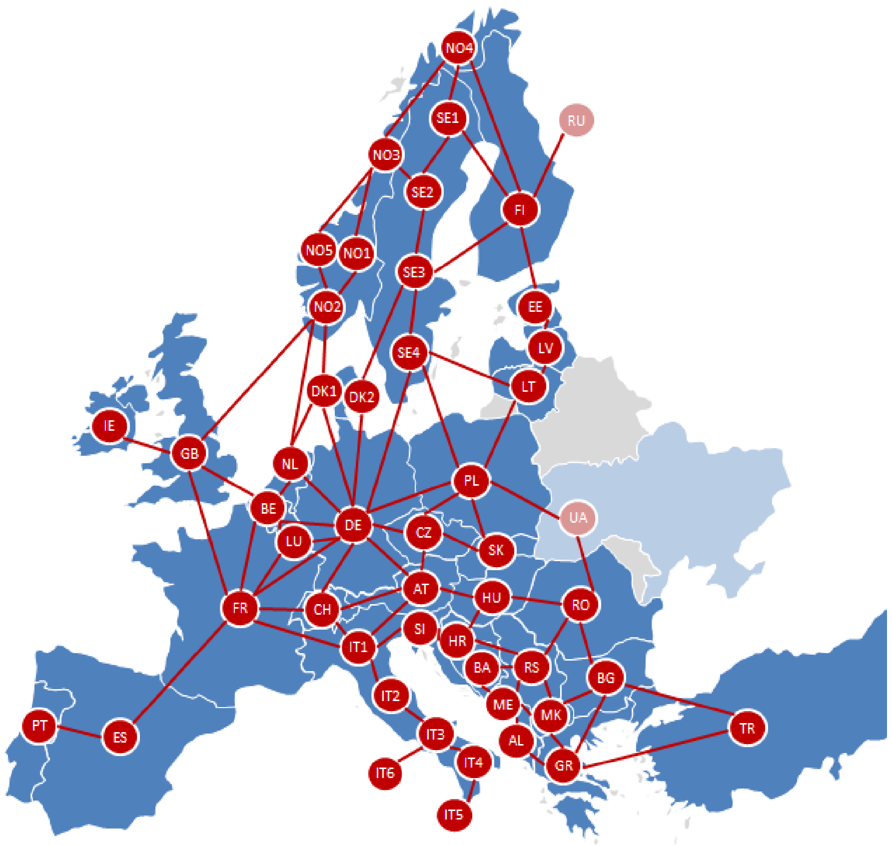
Flexible demand technologies



 Source: ENTSOE TYNDP 2024, CL analysis

Compass Lexecon pan-European power dispatch model covers the power markets of EU27 and neighbouring countries with fine granularity

Geographic scope of the model



- Compass Lexecon's power market model covers the **EU-27 countries as well as the UK, Switzerland, Norway, the Balkans and Turkey**.
  - The model is run on a commercial modelling platform Plexos® using data and assumptions constructed by CL Energy for demand, supply, commodity price and interconnection.
- Compass Lexecon's power market model constructs **supply in each price zone based on aggregated plants and simulates the market with hourly resolution**
  - European power plants database containing technical parameters of all thermal European plants
  - Zonal prices are found as the marginal value of energy accounting for generators' bidding strategies.
  - Model takes into account cross-border transmission and interconnectors and unit-commitment plant constraints.
- Compass Lexecon's power market model uses **ENTSOE Pan-European Climate Database (PECD)** for hourly time series for wind and solar production, hydro inflows and demand pattern.

 Source: CL

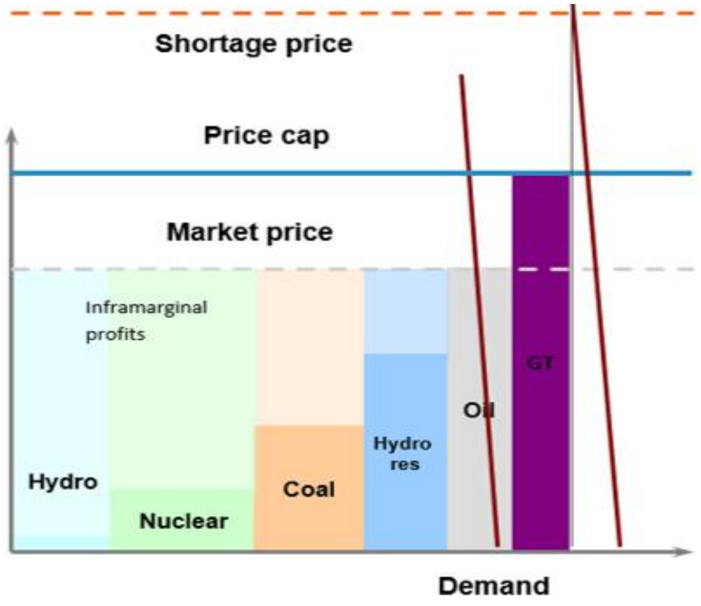
Compass Lexecon model relies on a combination of optimised long term capacity expansion and hourly generation dispatch

- Compass Lexecon model combines both long-term capacity scenarios based on energy policies and regulation and dynamic long-term optimisation through :

  1. **Long term capacity scenarios based on energy policies and regulation**:
     - **NECPs renewable development** until 2030
     - **Coal phase-out plan** through 2050
     - **European emission reduction** to net zero by 2050
     - National **power system reliability** through minimum margin

  2. **Dynamic long-term optimisation** : Based on cost reduction assumptions, the capacity mix is optimized to minimise the cost of the system while meeting several constraints such as security of supply or CO2 emission reduction target.

- **Compass Lexecon model constructs the hourly supply stack in each price zone based on aggregated plants unit commitment constraints:**
  - European power plants database containing technical parameters of all thermal European plants
  - Zonal prices are found as the marginal value of energy accounting for generators' bidding strategies
  - Model takes into account cross-border transmission and interconnectors



 Source: CL

Compass Lexecon's power market model is set up with a range of inputs derived from reference sources including TSOs, Regulators and the IEA

Key power price driver	Sources	Optimization
Demand		
Power demand	■ Long term electrification based on TYNDP 2024 De scenario	■ Fixed set as demand to be met
Supply		
RES capacity	■ Meet NECPs and EU-wide 60% RES-E penetration share by 2030 ■ RES potentials are based on ENTSOE TYNDP 2024 ■ CAPEX and OPEX outlook based on latest data from EC (April 2024)	■ Capacity dynamically optimised thereafter based NPV of anticipated costs and revenues under potential constraints
Nuclear capacity	■ Latest National plans on phase-down or phase-out ■ nucleareurope three nuclear capacity scenarios	■ Dispatch optimized by hourly dispatch model
Thermal capacity	■ Announcements from operators / National plans to phase-out or convert to biomass ■ Announcement on refurbishment and new projects in the short-term ■ CAPEX and OPEX outlook based on latest data from EC (April 2024)	■ Capacity dynamically optimised in the longer term based on NPV of anticipated costs and revenues ■ Dispatch optimized by hourly dispatch model
Storage technologies	■ CAPEX and OPEX outlook based on latest data from EC (April 2024)	
Commodity prices		
Gas	■ Forwards until 2024, convergence to IEA WEO 2023	■ Fixed set as an input (see appendix)
Coal ARA CIF	■ Forwards until 2024, convergence to IEA WEO 2023	■ Fixed set as an input (see appendix)
CO2 EUA	■ Forwards until 2024, convergence to IEA WEO 2023	■ Fixed set as an input (see appendix)
Interconnections		
Interconnection	■ ENTSO-E TYNDP 2022 outlook for new and existing interconnections	■ Fixed set as an input (see appendix)

Note: (1) MAF: Medium term adequacy forecast; (2) TYNDP: Ten Years Network Development Plan; (3) WEO: International Energy Agency World Energy Outlook

Power system total costs are compared using two modelling approaches across the different scenarios

Power system total costs are calculated for each scenarios in order to compare the impact of different nuclear capacity projections

4 components
- **CAPEX** (Capital expenditures) includes the difference in annualised investment costs in generation assets needed in the two scenarios
- **OPEX** (Operational expenditures) describes the difference in fixed and variable costs, excluding fuel and CO_2 costs. It includes maintenance costs, overhead
- **Fuel costs** describes the generation costs, excluding CO_2 costs that are not considered a system cost
- **Network costs** describe the difference in the network needs. More distributed renewable capacity leads to more network costs (CAPEX + OPEX)

Electricity system approach

In this approach:
- The modelling perimeter impacted by the different levels of nuclear development is limited to the electricity system
- Thus, a higher nuclear capacity is assumed not to impact any other energy vector, thus does not impact electricity demand

The higher level of nuclear development complements other sources of carbon free generation ensuring security of supply, for a given demand level.

This report presents the difference in system costs of the different scenarios.

Energy system approach (addition to the methodology used in previous studies)

In this approach:
- The modelling perimeter impacted by the different levels of nuclear development includes the broader European energy system
- In practice as an example, a higher nuclear capacity is assumed to substitute for low carbon H_2 imports, by allowing more domestic production of H_2 locally in the EU

The higher level of nuclear development goes along with a higher electricity demand, that reflects a higher level of European green H_2 production.

The difference in total system costs therefore includes an additional saving in costs from a lower level of H_2 imports in the EU.

4.

Modelling results

Electricity sector

In the #100GW scenario, a significant development of renewable capacity and storage is needed to achieve a Net Zero economy by 2050

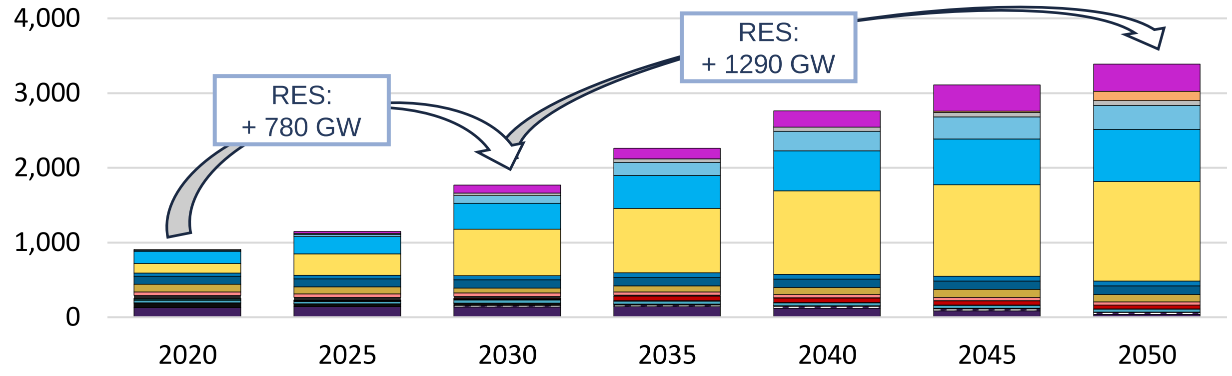
Achieving Net Zero by 2050 requires a fast development of renewables, as well as short- and long-term storage

- 780 GW of additional RES capacity* is projected in the #100GW scenario between 2020 and 2030, reaching 1220 GW by 2030
- This is consistent with the objectives defined in the REPower EU target of c. 1200 GW of renewable capacity by 2030
- Additional 1290 GW more RES capacity is then projected to be developed in order to reach a net-zero economy by 2050
- This RES development is necessarily accompanied by short term and long-term storage (resp. batteries and Power-to-gas in our modelling) to integrate the energy optimally

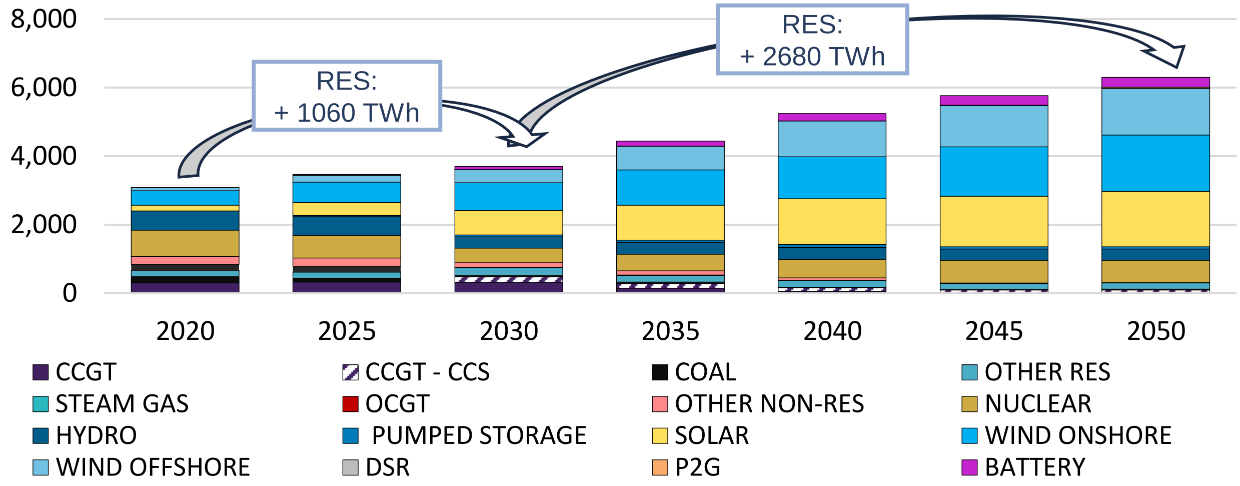
In generation terms, the European Union aims at a share of 66%-69% of renewable in the system by 2030

- In the #100GW scenario, the projected capacity mix results in 69% of electricity supplied by renewables in 2030 and 87% by 2050.
- The 2030 targets in terms of share of renewable electricity from NECPs (66%) and REPowerEU targets (69%) are therefore met.
- Renewable penetration is projected to further increase by 2050 to reach a net-zero economy.

Total installed capacity – #100GW scenario, 2020-2050 [GW]



Generation mix – #100GW scenario, 2020-2050 [TWh]



Source: CL analysis

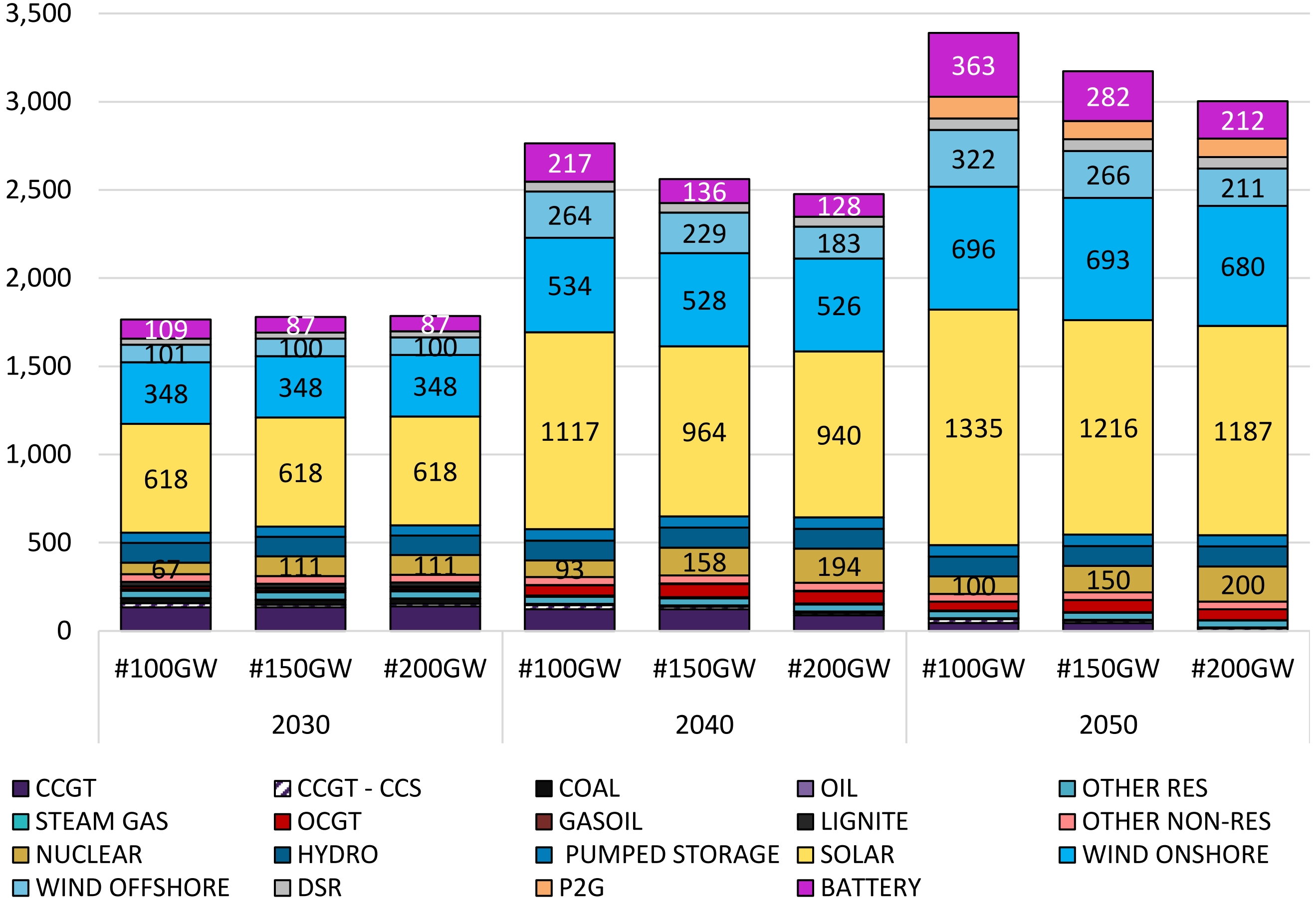
*Notes: *This refers to net additional capacity, in excess of the capacity built to replace decommissioned capacity*

Higher nuclear capacity could complement renewables and flexibility resources to reach Net Zero

Higher nuclear power contributes to system flexibility and thus complement RES, flexible resources and storage development to reach Net Zero by 2050

- Nuclear technology is dispatchable and operates at relatively low marginal costs and provides firm and flexible capacity to the system.
- A strong and sustained pace of RES and flexible capacity development is required in the #100GW scenario (+85GW per year).
- Additional nuclear development complements the required RES and flexible capacity development necessary to reach net zero in 2050.
- This corresponds to an equivalent of c180 GW of RES capacity and c100 GW of flexible capacity in the #150GW scenario and a reduction of c280 GW of RES capacity and c170 GW of flexible capacity in the #200GW scenario.
- This diversification of the mix at iso-demand allows for a lower reliance on renewables and batteries, that may relieve some pressure on supply chains. It also leads to total cost benefits as explained later in this report.

EU 27 installed capacity, power system approach – all scenarios, 2030-2050 [GW]



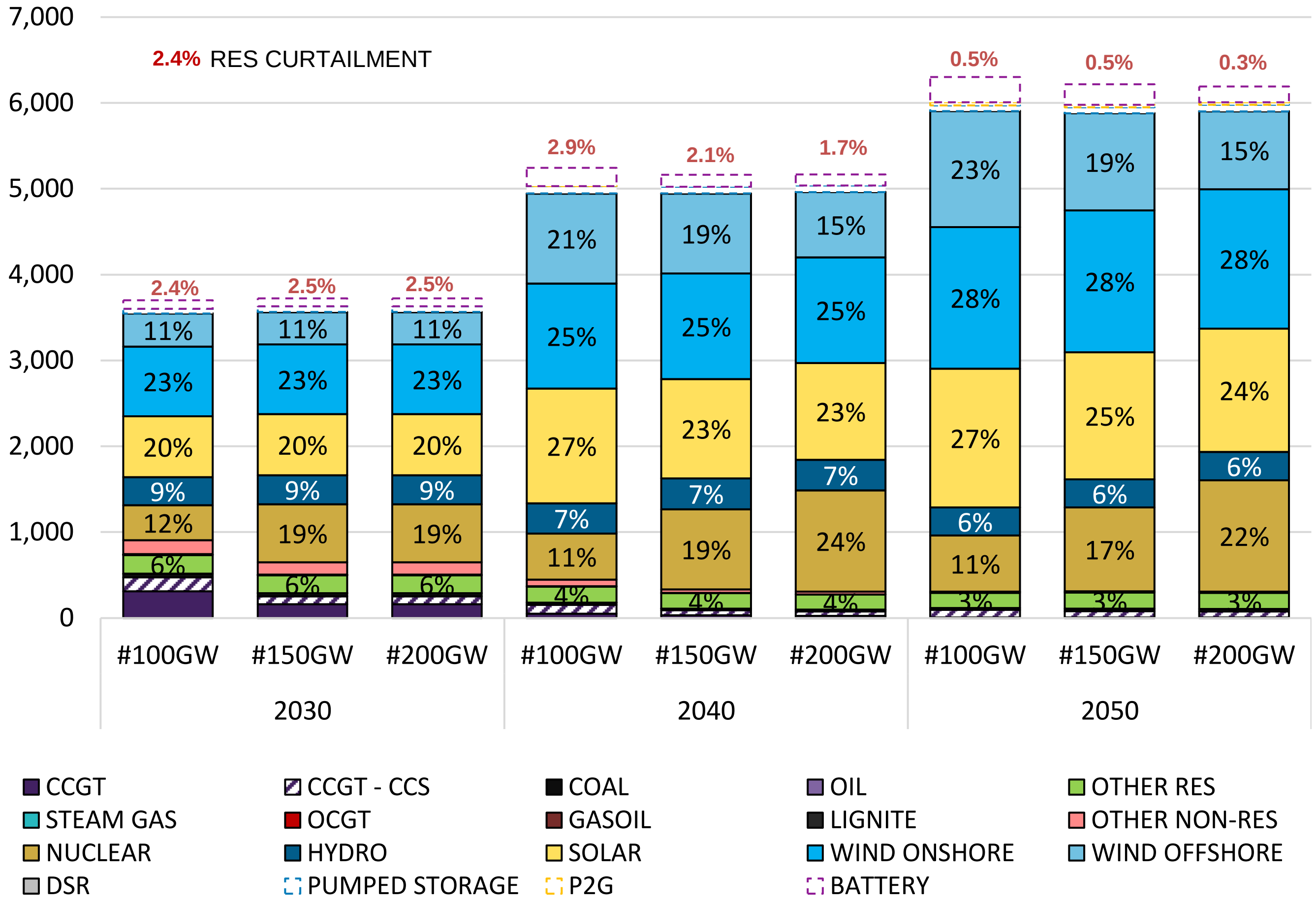
 Source: CL analysis

Higher nuclear generation could complement renewable and storage to reach Net Zero and reduce renewable curtailment

Higher nuclear power contributes to diversify the generation mix and to reduce “cannibalisation” of RES as well as RES curtailment

- Higher nuclear generation allows to diversify the generation mix required to reach net zero by 2050.
  - Renewable generation amounts to 80% and 75% respectively in the #150GW and #200GW scenario in 2050 instead of 86% in the #100GW scenario.
  - Nuclear generation share rises from 11% in the #100GW scenario to 17% and 22% respectively in the #150GW and #200GW scenario.
- From 2040 onwards, a higher nuclear capacity also leads to lower “cannibalisation” of RES and a lower amount of renewable energy being curtailed (both in absolute and relative terms)

EU 27 generation, power system approach – all scenarios , 2030-2050 [TWh]

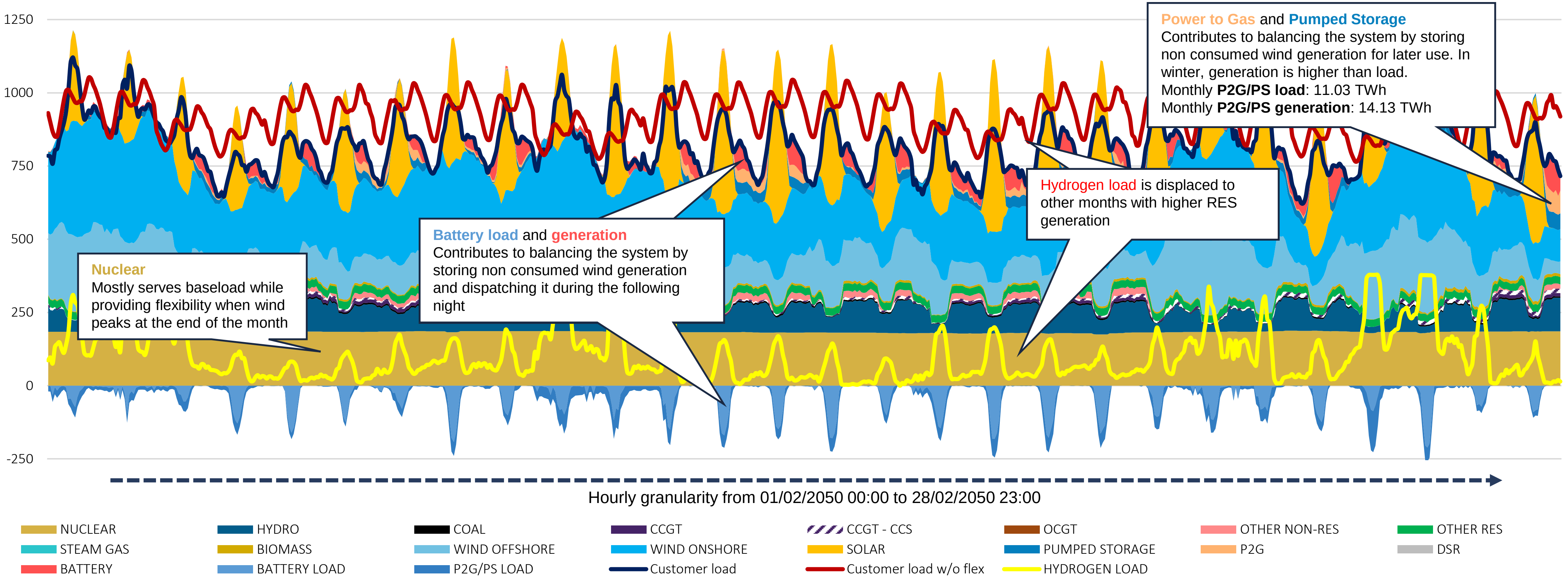


 Source: CL analysis

Case study

In winter 2050, nuclear continues to operate baseload as excess RES production is absorbed by storage & P2G/PS

Hourly generation mix during a winter month (GWh/h) – February 2050 - #200GW scenario

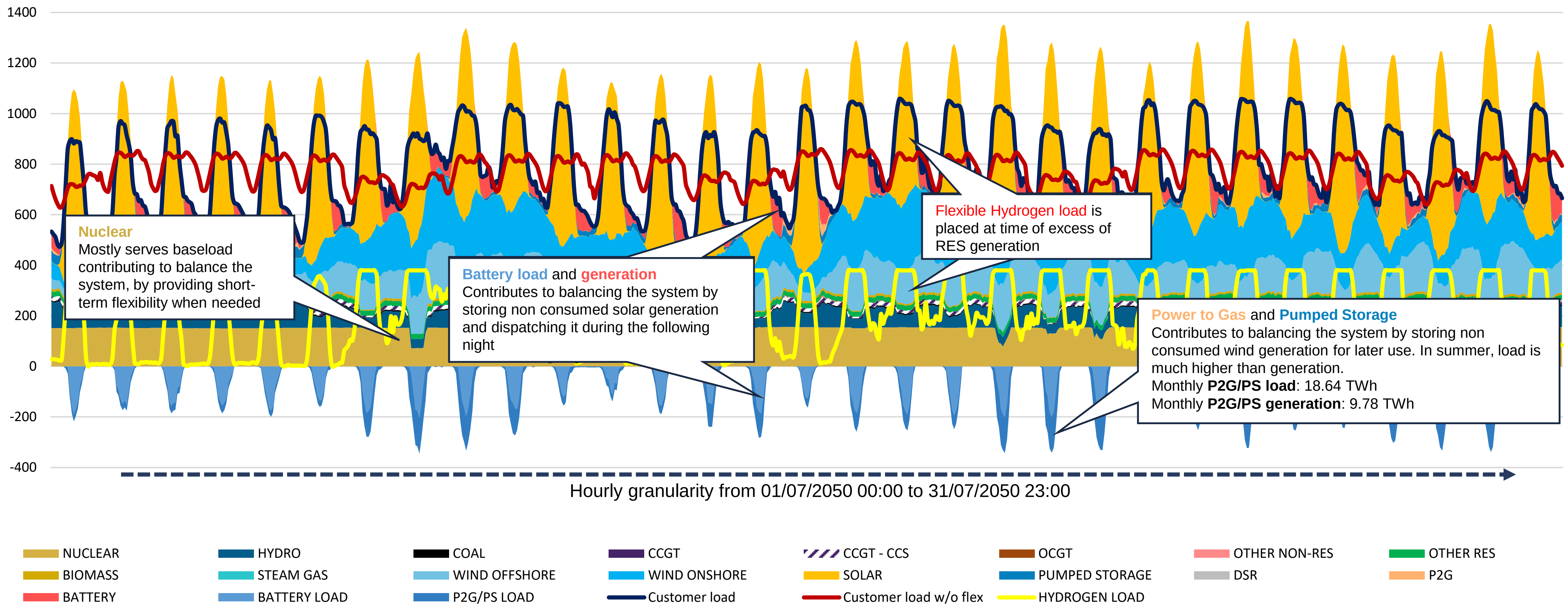


 Source: CL analysis

Case study

In summer 2050, nuclear generation cycles during the day to provide flexibility to the power system, to complement RES generation

Hourly generation mix during a summer month (GWh/h) – July 2050 - #200GW scenario

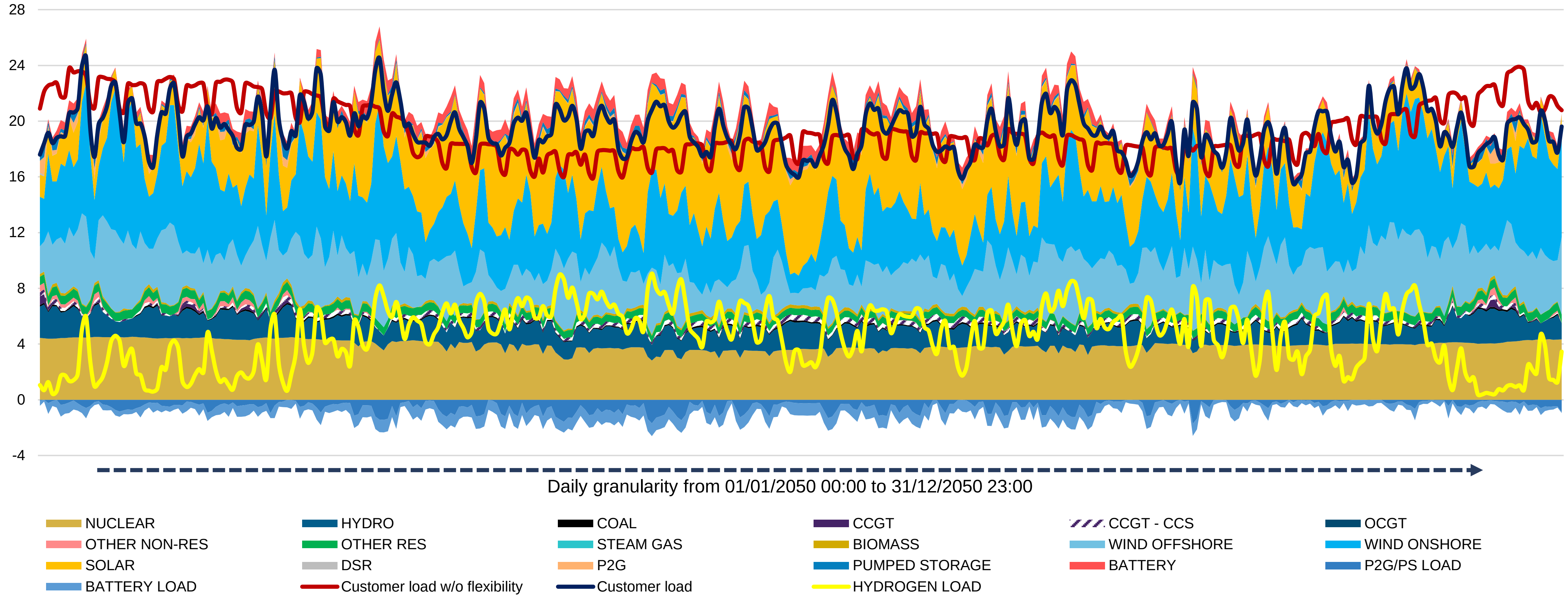


 Source: CL analysis

Case study

Over the full year 2050, nuclear generation complements RES and flexible resources by providing low carbon short- and long-term flexibility

Daily generation mix and Hydrogen load (TWh/day) – Year 2050 - #200GW scenario



 Source: CL analysis

Higher nuclear capacity drives EU power prices down between 2025 and 2040, before converging in all scenarios by 2050

In the short-run (2025 to 2030):

- Nuclear trajectories are similar in the #150GW and #200GW scenarios, being more ambitious than the #100GW scenario in terms of nuclear development.
- This brings low marginal cost generation in the power system, decreasing average power prices

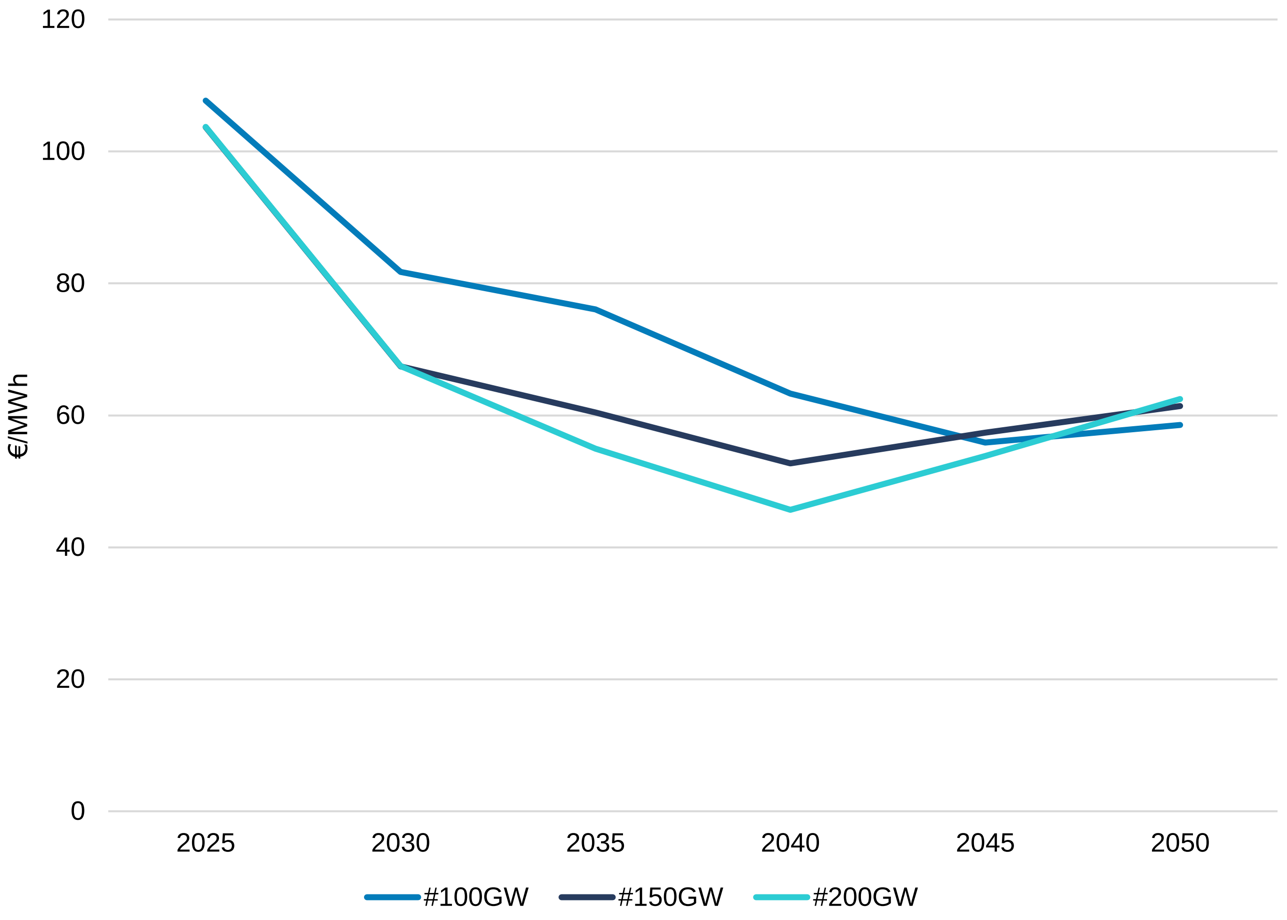
In the medium-run (2030 to 2040)

- The higher development of nuclear capacity drives the prices even lower in the #200GW scenario
- However, the climate targets becoming more stringent by 2040 in all scenarios, average power prices decrease in all scenarios due to increasing renewable development.

In the longer-run (2040 to 2050)

- All scenarios achieve Net-Zero by 2050.
- With increasing demand and RES capacities in the long term, supply and demand flexibilities are more frequently setting the price, leading to price convergence across the scenarios.

Power prices in the EU in the three scenarios (in €, real 23 / MWh)



 Source: CL Energy analysis

#100GW scenario would reduce the residual value of investments by €658b in 2050 compared to #200GW (resp. €222b compared to #150GW)

The #100GW scenario would increase investment cost by €183 billion over the #200GW scenario (resp. €151b over the #150GW scenario)

- Anticipated nuclear closure would save €18b (resp. €6b) in the short to medium term before increasing investment cost by €201b (resp. €157b) in the long term.

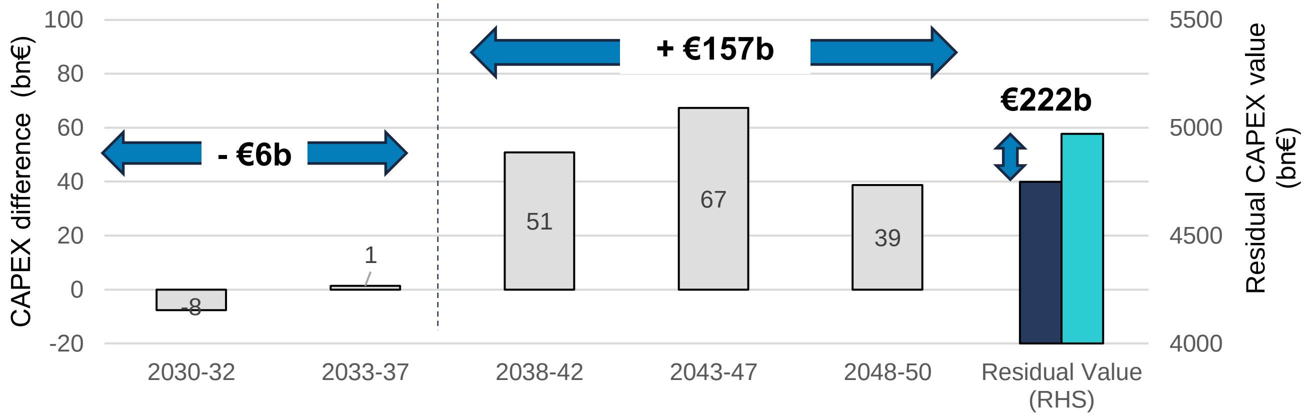
The #100GW scenario would decrease the residual value of investment by €658b in 2050 compared to the #200GW scenario (resp. €222b compared to the #150GW scenario)

- The #200GW and #150GW scenarios assumes new nuclear builds toward the end of the horizon, which have a longer lifetime than other clean technologies, and induces investments for a longer period than the modelling horizon.

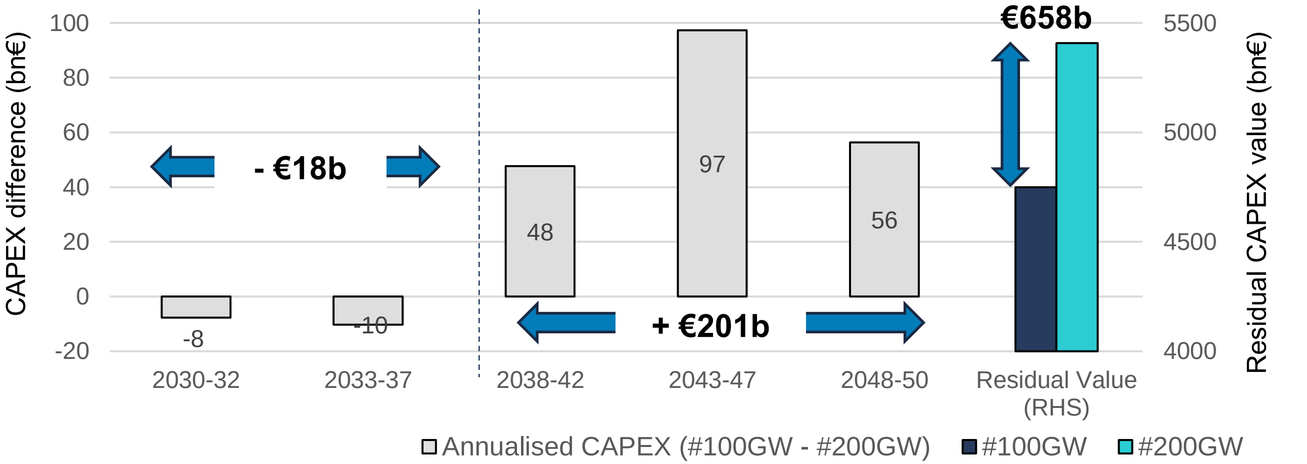
Note: As new capacity built during the horizon may have a lifetime that exceeds the end date of horizon (e.g. Nuclear capacity with longer lifetime), there is a part of their investment cost which is not considered in the investment cost differences year by year. These remaining capital annuities of the investment cost are the residual value of a given asset and are summed for all asset still existing after the horizon to form the residual value of investment on the right axis of the graph.

We note that in practice a more accurate assessment of the residual value would have to consider the specific market and regulatory framework in each MS.

Annualised CAPEX and residual value, 100# vs 150# difference (in bn€, real 23)



Annualised CAPEX and residual value, 100# vs 200# difference (in bn€, real 23)



 Source: CL Energy analysis, CAPEX from CE 2024 impact assessment

Higher nuclear generation lowers gas-fired power generation by ~40%, especially during the transition (2031-2040)

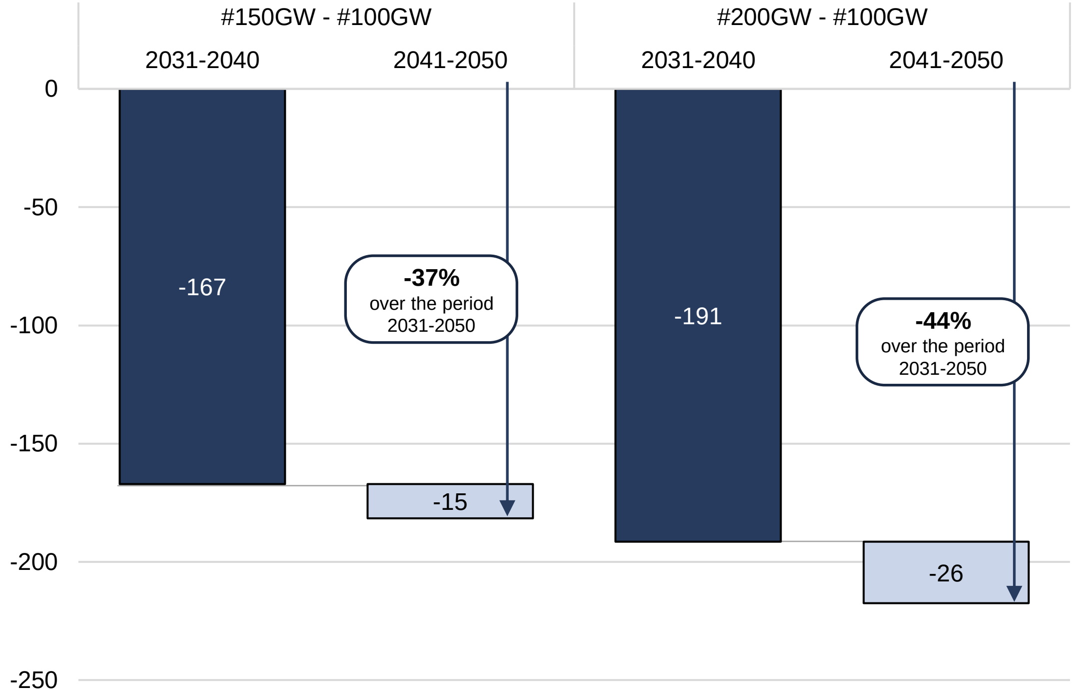
Going from a strategy at 100GW to 150GW nuclear capacity in the EU leads to 181 bcm of Natural Gas consumption saved on the 2031-50 period

- That represents 37% of total Natural Gas consumption in the #100GW scenario over the same period
- With the large majority of the savings occurring between 2031 and 2040

Going from a strategy at 100GW to 200GW nuclear capacity in the EU leads to 218 bcm of Natural Gas consumption saved on the 2031-50 period

- That represents 44% of total Gas-based electricity production in the #100GW scenario over the same period
- With the large majority of the savings occurring between 2031 and 2040

Avoided EU Natural gas consumption 2031- 2050 (bcm/year)



Note: Note: reduction of Natural Gas consumption is calculated on the basis of production in the #100GW scenario
Source: CL Energy analysis

Additional nuclear generation enables to reduce CO2 emissions during the transition and helps to achieve the 2040 emission reduction target

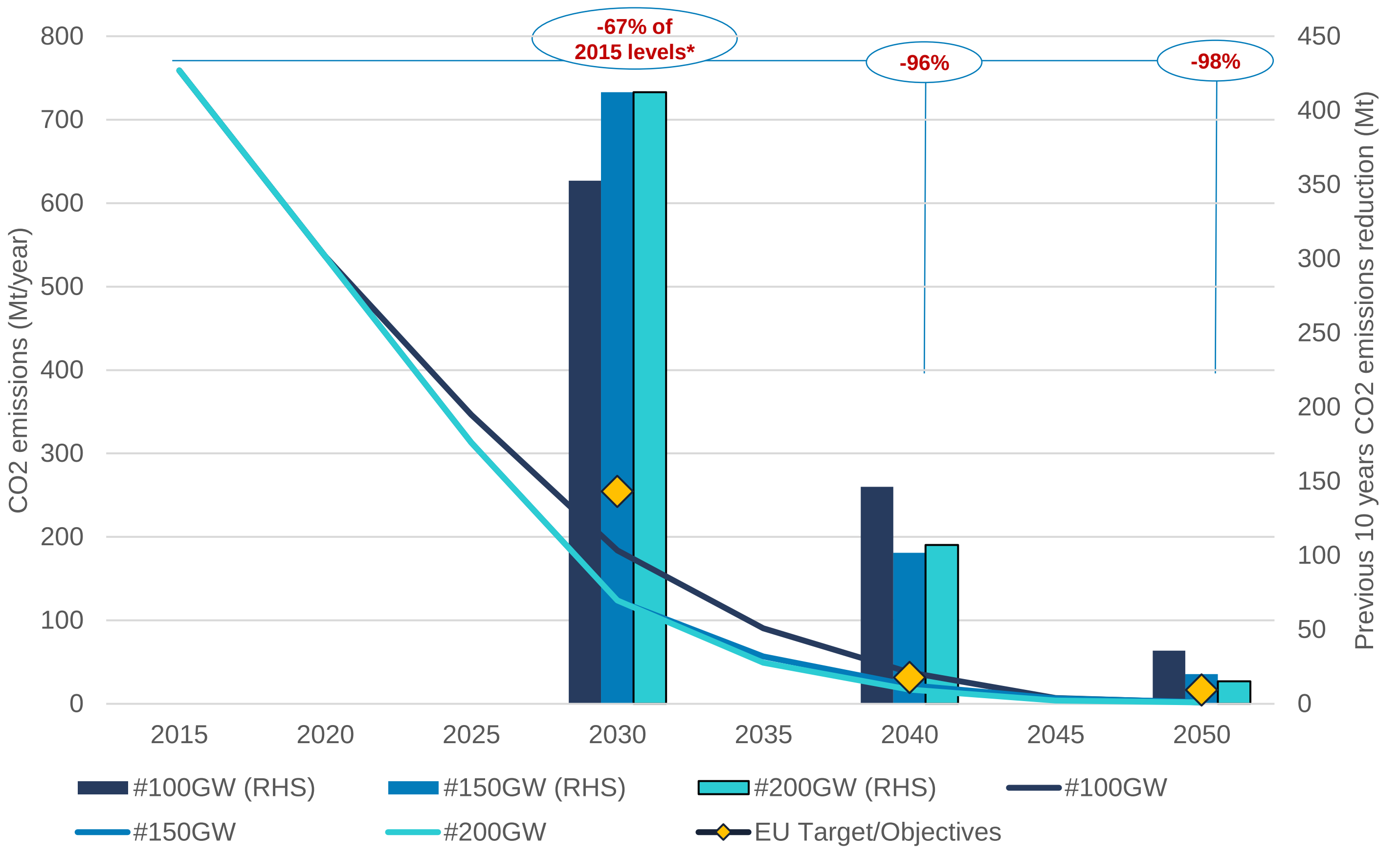
Additional nuclear capacity in the EU leads significant CO2 emissions savings, particularly over the period 2030-2040

- Additional nuclear capacity is projected to reduce average CO2 emission by -36 MtCO2/year in the #150GW scenario over 2030-2040 (resp. -41 MtCO2/year in the #200GW scenario).
- This corresponds to a total reduction of 430 MtCO2 in the #150GW scenario, i.e. 35% reduction (resp. 500 MtCO2 in the #200GW scenario, i.e. 41% reduction).

Additional nuclear capacity in the EU is projected to help reach 2040 targets

- The EU "Impact assessment report for 2040 climate target mentions power system objectives of "limited remaining CO2 emissions" or "close to decarbonised" by 2040
- Additional nuclear capacity is projected to help reach this target, by reducing power system emissions by 41% in the #150GW scenario in 2040 (resp. 58% in the #200GW scenario)

Power system emissions and emission targets (in Mt)



*Notes: *Targets displayed are for the power sector only (excluding District heating and own uses). It is not fully decarbonised as it excludes carbon absorption from Land-Use, Land Use Change and Forestry (LULUCF).*
Source: European Commission, Europe 2040 climate target impact assessment. Scenario S2, CL Energy analysis

Additional nuclear capacity leads to higher OPEX, but lower total system costs, in particular due to lower network reinforcement costs

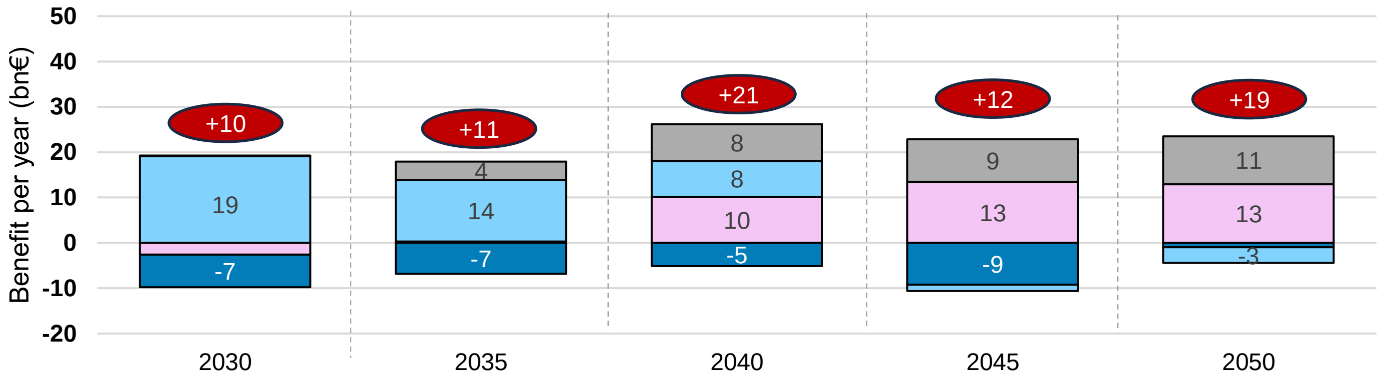
The scenarios with a higher nuclear capacity lead to overall lower system costs

- In the short run, higher nuclear capacity leads to slightly higher CAPEX costs due to the higher investments in nuclear. This additional nuclear capacity mostly displaces thermal power plants in the merit order, leading to significant fuel costs savings.
- In the longer term, nuclear capacity is assumed for modelling purposes to replace an alternative capacity mix of RES and flexible resources. This reduces CAPEX spendings and overall system costs as RES marginal contribution to security of supply decreases with installed capacity.

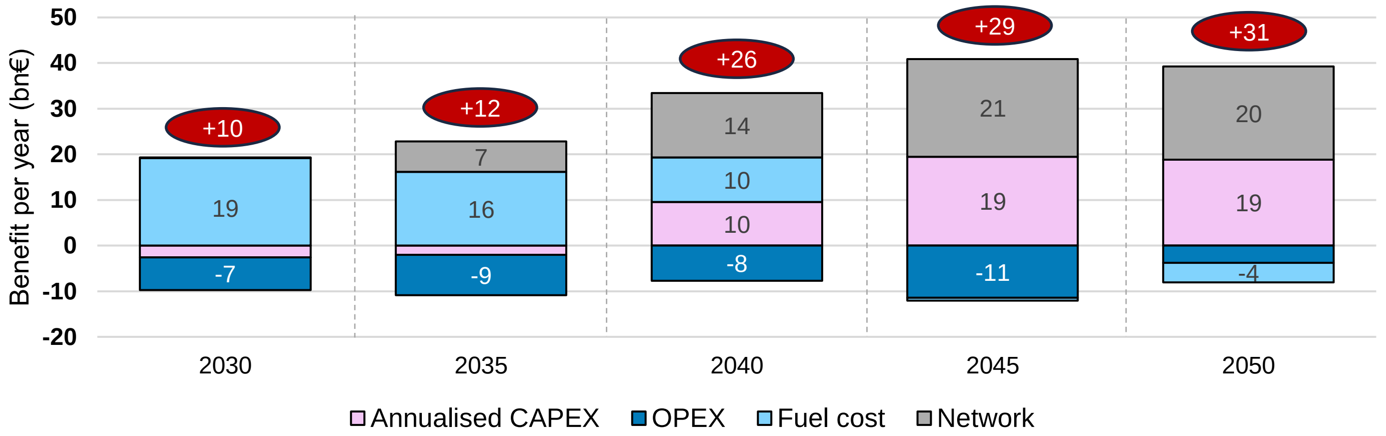
The benefits are higher in the #200GW scenario, particularly towards the end of the modelling horizon

- The #200GW scenario shows a higher level of benefits than the #150GW scenario in the long term (37 €bn/year in 2050 compared to +25 €bn/year in the #150GW scenario).
- These higher benefits originate from higher CAPEX savings, slightly mitigated by higher OPEX and fuel cost, but leading to a net benefit.

Total yearly costs benefit in the #150GW scenario vs #100GW (in € billion, real 23 / year)



Total yearly costs benefit in the #200GW scenario vs #100GW (in € billion, real 23 / year)



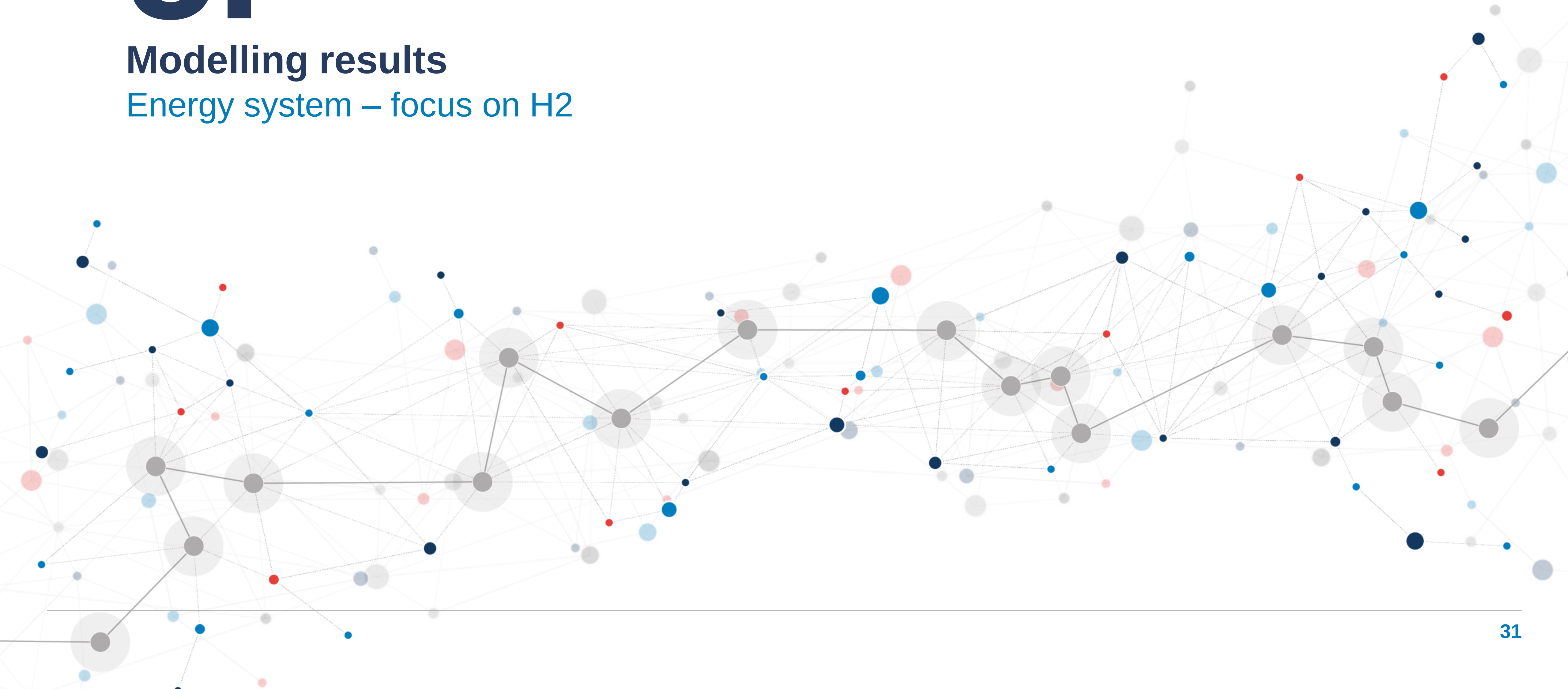
Source: CL analysis

** CAPEX for asset with a long economic lifetime like nuclear (60 years) can be spread over a longer time that renewable energy (25 years for wind and solar), and therefore lead to lower annualised cost, everything being equal.*

5.

Modelling results

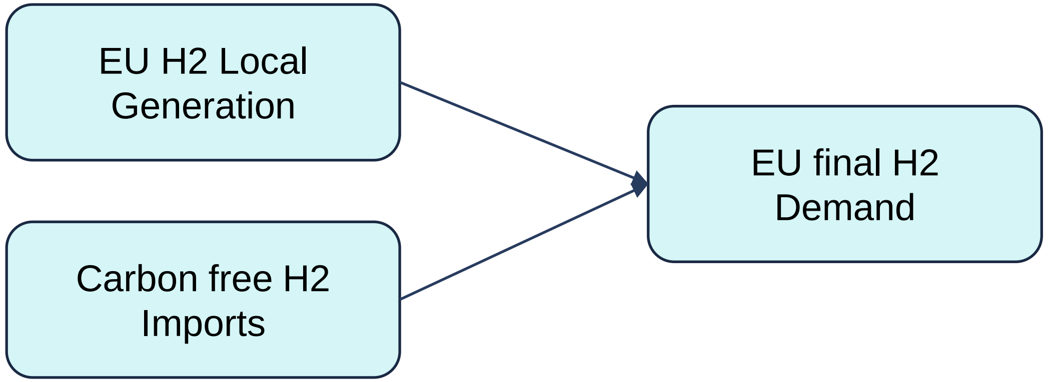
Energy system – focus on H2



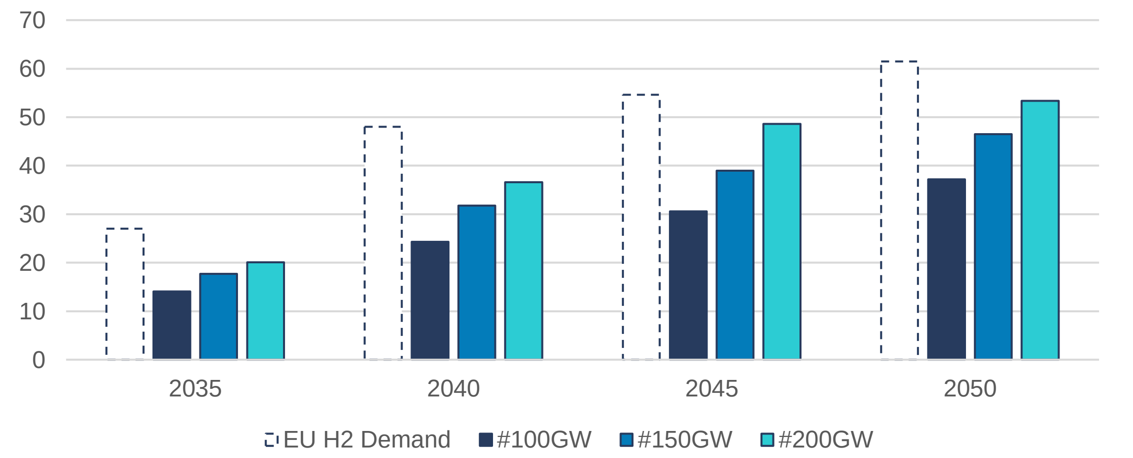
Description of the energy system approach

Supporting nuclear development with local H2 production could lead to economic benefits

- Carbon free Hydrogen will play an important role in the decarbonisation of the EU energy system.
  - Domestic of Carbon free Hydrogen is projected to increase across the EU, but significant imports are likely to be needed to meet demand.
- In the energy system approach, the final H2 demand in the EU is assumed to be the same than in the electric system:
  - However, the carbon free H2 local production from electrolysis is assumed to be higher in the scenarios with a higher nuclear capacity as more low carbon generation is available for the broader energy system at the expense of lower H2 imports.
  - In turn, the carbon free H2 local production in the #100GW scenario is therefore the same as in the electric system approach, while it is higher in the #150GW and #200GW scenarios
- NB: In the electricity system approach presented in the previous section, green H2 production in the EU was assumed to be the same in all scenarios, and consistent with TYNDP 2024 assumptions of production and imports.



EU H2 local generation, energetic system approach [Mt H2]



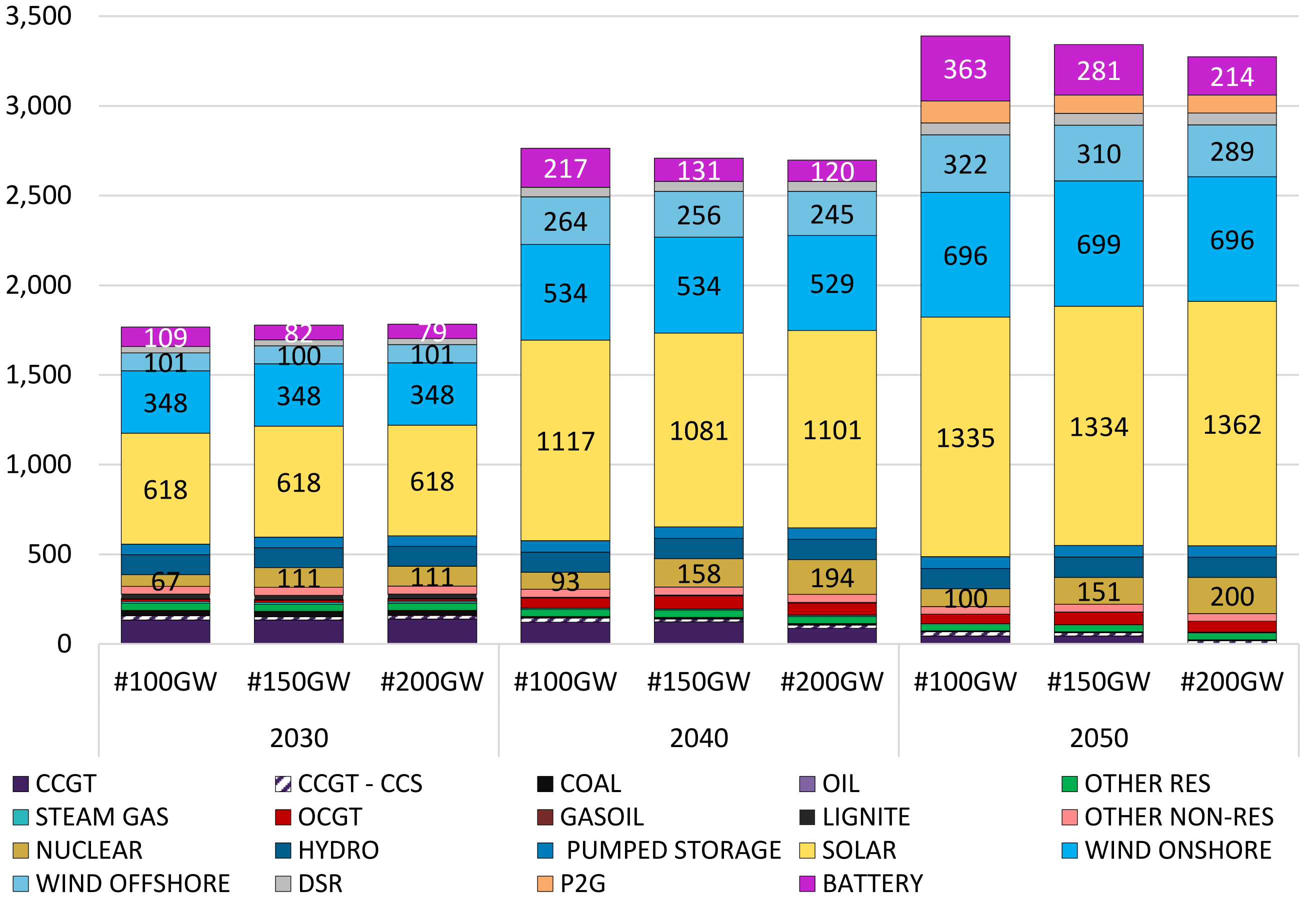
 Source: CL analysis

Additional nuclear capacity allows to reduce H2 imports from outside EU

In the energy system approach, additional nuclear capacity allows to reduce H2 imports from outside EU

- In the energy system approach the extra green H2 production in the EU described in the previous slide, is produced from the additional available low carbon generation in the #150GW and #200GW scenarios.
- To meet the increased total demand in these scenarios, the system needs a comparable renewable capacity with the #100GW scenario, but lower flexible capacity, as flexibility is provided by the combination of additional nuclear capacity and electrolysers.
  - In the #150GW scenario, flexible capacity reduces by 100 GW while nuclear capacity increase by 50 GW in 2050
  - In the #200GW scenario, flexible capacity reduces by 170 GW while nuclear capacity increase by 100 GW in 2050

EU 27 installed capacity, power system approach – all scenarios, 2030-2050 [GW]



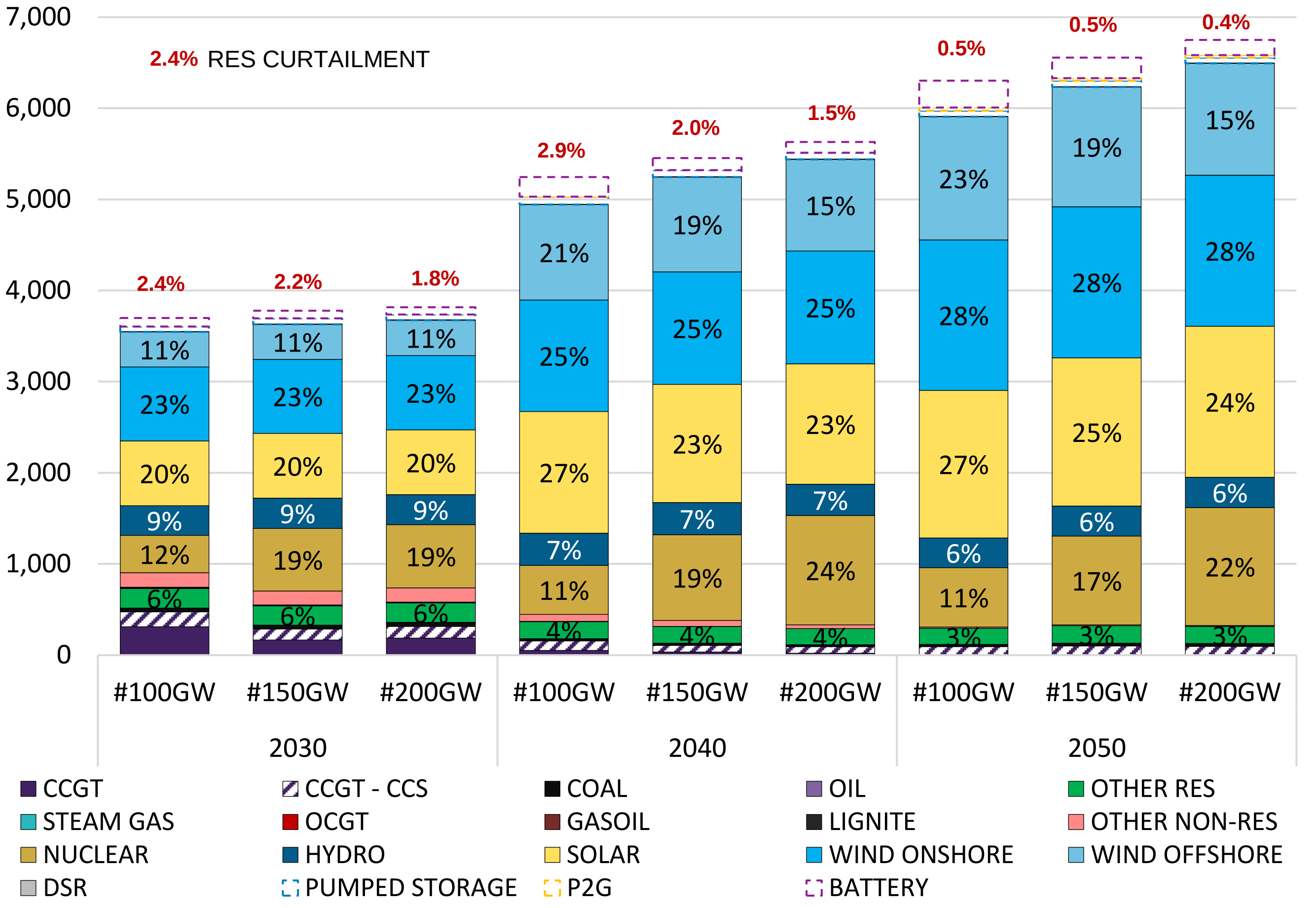
 Source: CL analysis

Additional nuclear generation allows to reduce H2 imports from outside the EU

In the energy system approach, additional nuclear generation allows to reduce H2 imports from outside EU

- In the #100GW scenario, 18800 TWh of low carbon generation is used to produce 460 Mt of green H2 is through electrolysis in the EU between 2030 and 2050, representing 55% of EU total H2 demand projected by TYNDP 2024.
- In the #150GW scenario, the additional nuclear capacity allows to produce 5100 TWh of additional low carbon generation, thus 125 Mt additional green H2 in the EU over 2030-2050, bringing local production to 70% of EU total H2 demand over that period, thus decreasing imports by 33%.
- In the #200GW scenario, the additional nuclear capacity allows to produce 9300 TWh of additional low carbon generation, 230 Mt additional green H2 in the EU over 2030-2050, bringing local production to 82% of EU total H2 demand over that period, thus decreasing imports by 61%.

EU 27 generation, power system approach – all scenarios , 2030-2050 [TWh]



Note: Electrolyser efficiency is assumed to reach 85% by 2050, based on ENTSOE TYNDP 2024.

Source: CL analysis

Additional nuclear capacity leads to benefits, whether it is standalone or used to enable local generation of H2

Across the different scenarios, total system costs between the different scenarios are defined as:

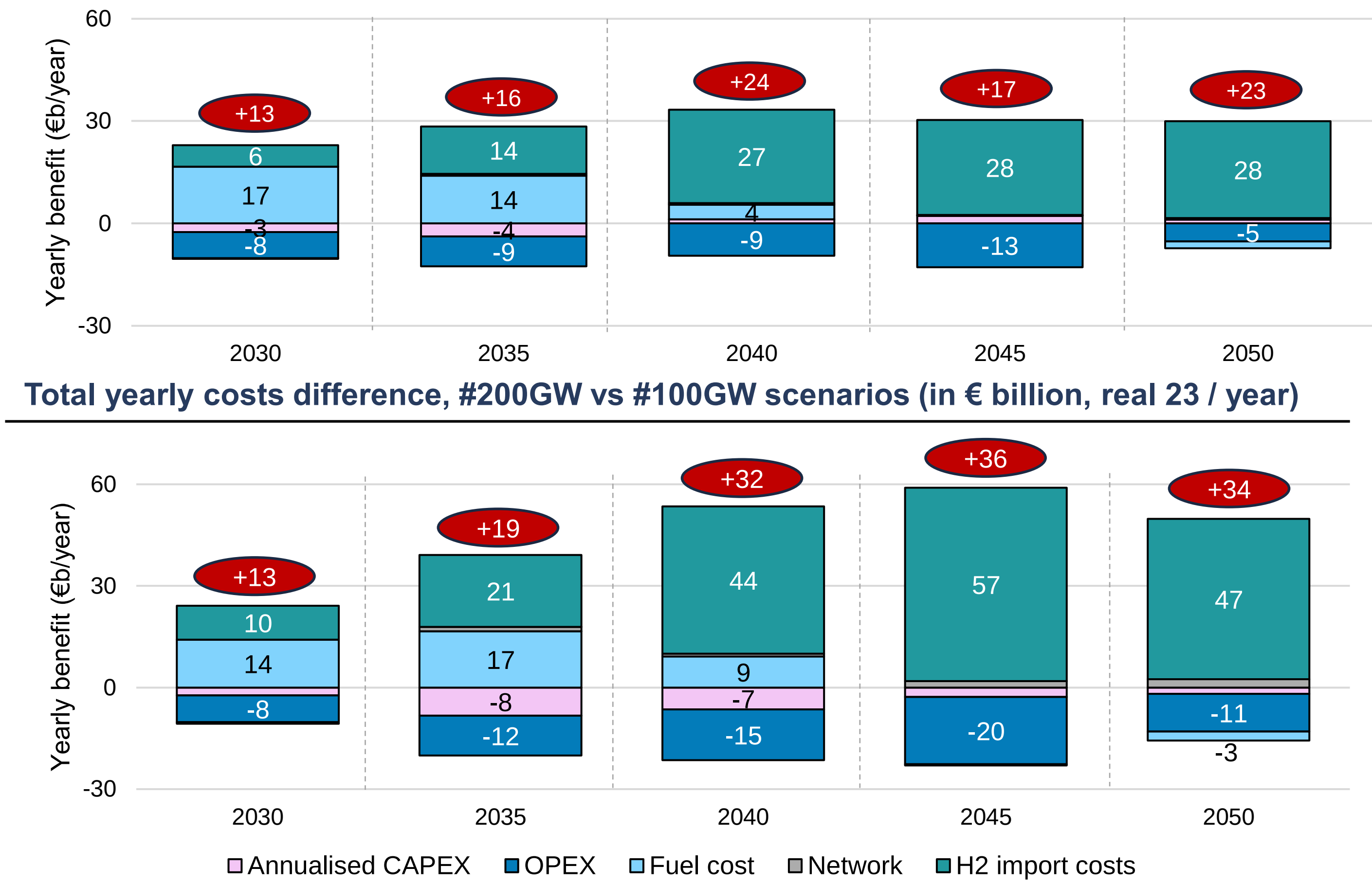
- CAPEX includes the difference in annualised investment costs in generation assets needed in the two scenarios
- OPEX describes the difference in yearly fixed costs
- Fuel costs describes the generation costs, excluding CO_2 costs that are not considered a system cost
- Network costs describe the difference in the network needs. More distributed renewable capacity leads to more network costs (CAPEX + OPEX)
- H2 import costs describe the savings from import a lower volume of H2, due to more production in the EU

The scenarios with higher nuclear capacity lead to lower overall system costs

- Because of a higher H2 production in the EU in the scenarios with more nuclear capacity, the generation mixes differ less than in the electric system approach to match the increase in demand
- This causes less difference in CAPEX, the main difference coming from H2 import costs, and creating a net benefit reflecting a lower cost of producing H2 locally

Total yearly costs difference, #150GW vs #100GW scenarios (in € billion, real 23 / year)

Total yearly costs difference, #200GW vs #100GW scenarios (in € billion, real 23 / year)



 Source: CL analysis

Additional nuclear capacity leads to additional benefits, if used to enable generation of H2, thereby limiting imports

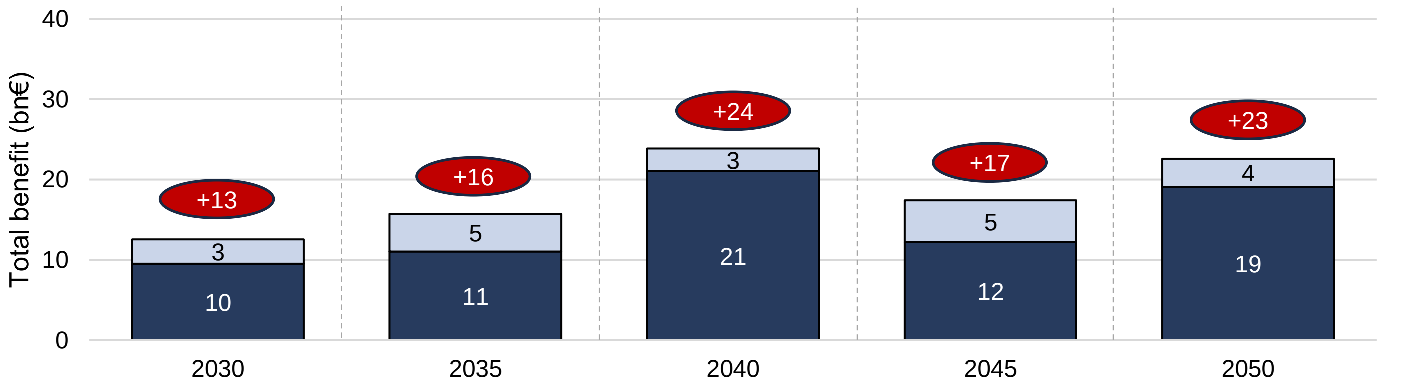
An energy system approach leads to more benefits that the electric system alone

- Optimising energy system operation in a scenario with more nuclear capacity, by producing a higher volume of H2 through electrolysis, leads to more economic benefits than a pure electric system approach
- This extra benefit is explained by the cost of importing H2 from abroad being higher, in a scenario with more nuclear, than the total costs of producing it in the EU

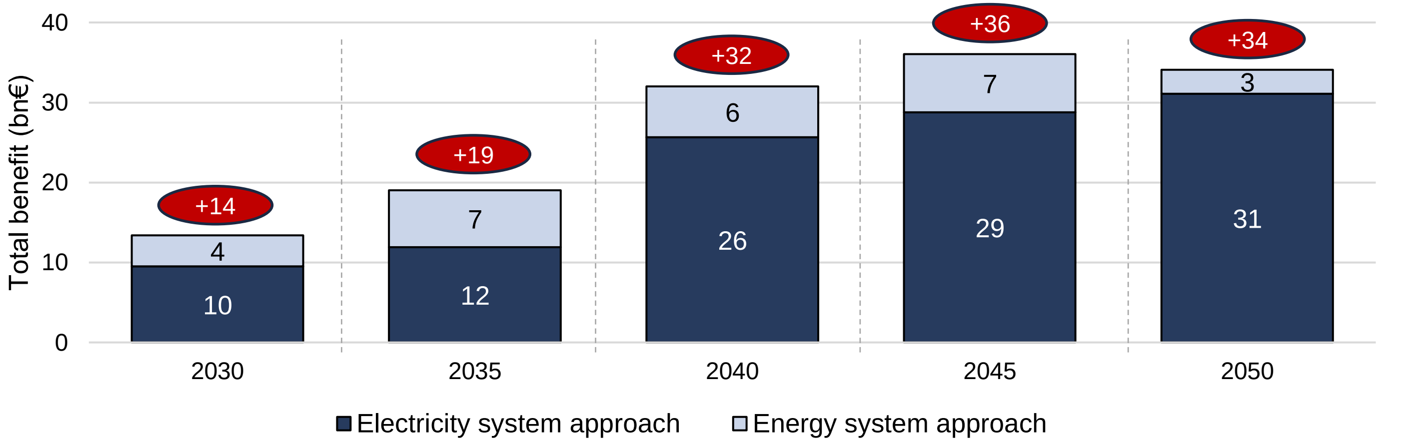
The benefit is higher with a higher nuclear capacity

- The total benefits reaches €83bn extra in the period 2030-2050 in the #150GW scenario, which is a 27% premium compared to the electric system approach
- In the #200GW scenario the benefits from accounting for benefits linked to H2 local production are higher, amounting to an extra €125bn on the period 2030-2050, corresponding to a premium of 27% compared to benefits in the electric system approach

Total benefits per approach, #150GW vs #100GW scenarios (in € billion, real 23 /year)



Total benefits per approach in the #200GW scenario vs #100GW (in € billion, real 23 /year)



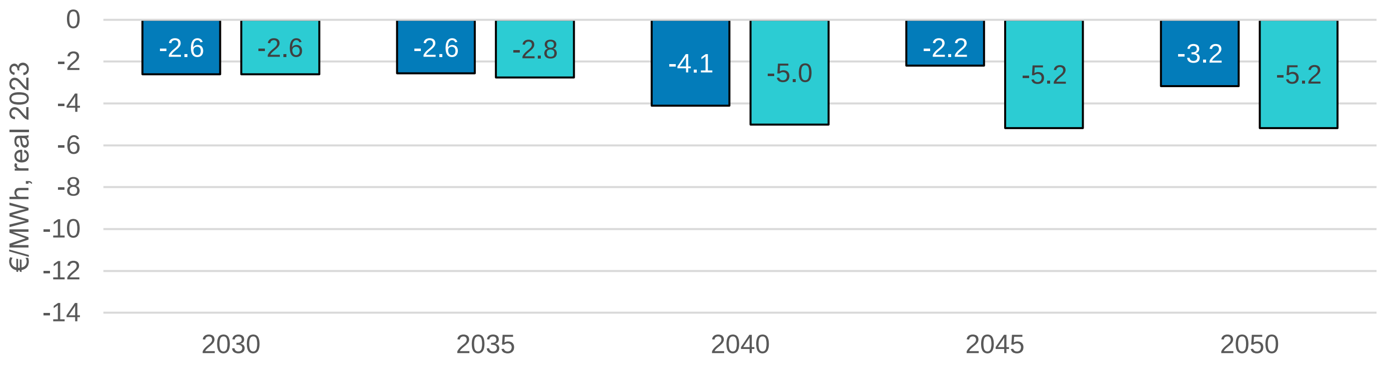
Note: H2 import cost is assumed to be at 5 €/kg H2 in 2030, decreasing to 4 €/kg H2 in 2050, real 2023.
Source: CL analysis
.

Additional nuclear capacity leads to lower levelized cost of power generation in both approaches

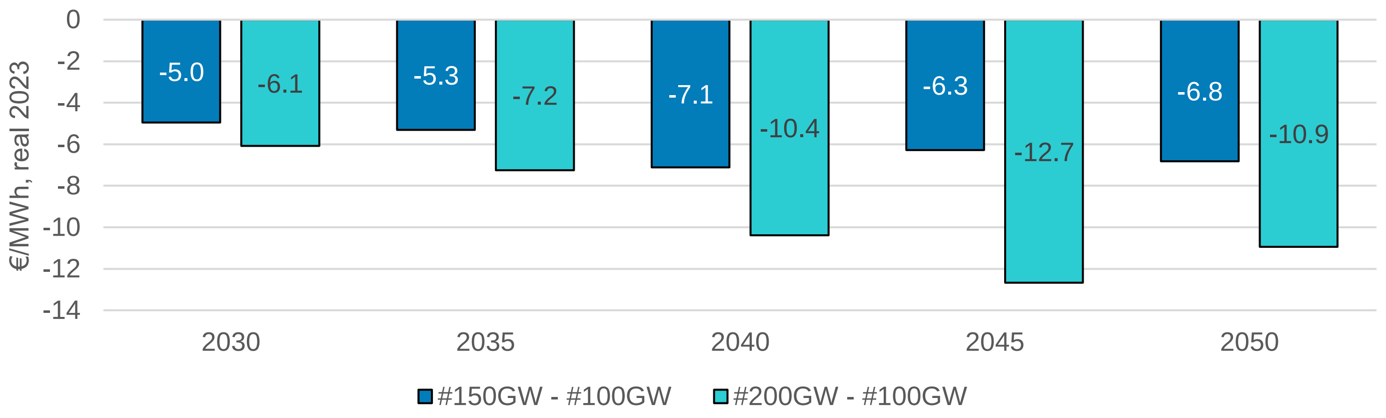
- **Levelized cost of power generation is lower with a higher level of nuclear capacity**
  - The levelized cost of power generation is defined as the total cost of electricity generation divided by the demand, i.e. the total cost of generating a MWh of power (including fuel, investment, networks, OPEX, but without CO2 cost of benefit associated with lower H2 imports)
  - In both approach, we observe lower levelized cost of power generation with a higher installed capacity of nuclear power, with or without an increase in H2 local generation

- **The benefits are higher in the energy system approach, reflecting a lower cost of generation for satisfying a higher level of demand**
  - In the energy system approach, in which we consider a higher level of demand in #150GW and #200GW scenarios, we observe a higher difference in levelized cost of power generation with the #100GW scenario.
  - We haven't accounted for the cost benefits of importing less hydrogen, and solely focused on the cost of power generation

Diff. in levelized cost of generation - electricity system approach (in €/MWh, real 23 / year)



Diff. in levelized cost of generation - energy system approach (in €/MWh, real 23 / year)



Source: CL analysis

Note: Levelized cost of power generation is defined as power system total cost divided by final direct or H2-related power consumption and is a proxy to assess the impact on unitary cost of power generation and power network for the end customer.

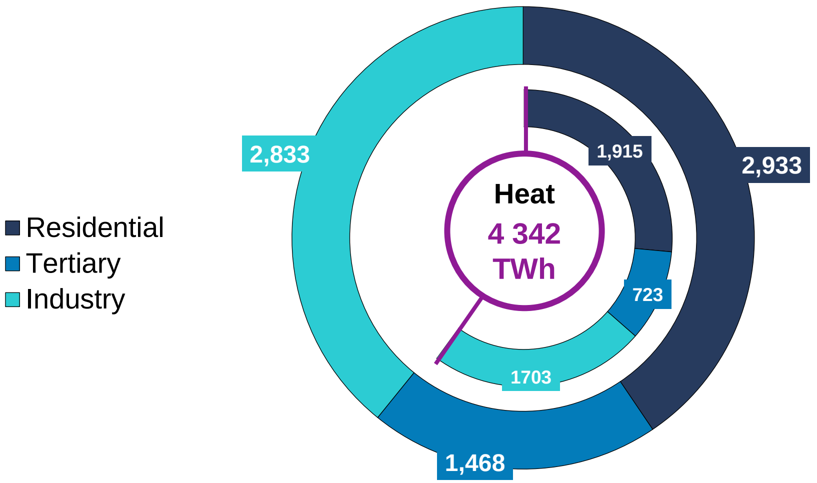
6.

SMR case study: Industrial Heat sector decarbonisation

Context: In 2021, almost 60% of the final energy consumed in the EU went to heating, of which almost 70% is still to be decarbonised

To reach Net Zero, decarbonised heat will be needed to complement electrification of end uses.

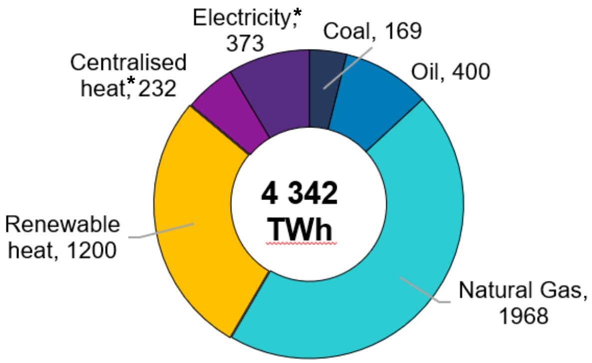
Share of uses in final energy consumption in the EU in 2021, in TWh[1]



60% of final energy is consumed as heat in the EU

- In 2021, final energy consumption in the EU amounts to **7 234 TWh**, of which **60% of heat, i.e., 4 342 TWh,** considering all sectors (residential, tertiary, industrial).
- Heating for residential and tertiary account for a total of 2 638 TWh in 2021[1] while industrial heat demand amounts to a total of 1703 TWh
- In the later sections of this report, SMRs are assumed to be fit for heat supply **for industrial demand with temperatures < 500C**
  - Indeed, industrial heat demand is more adapted for SMR as it is less seasonal than residential heat demand

Heat sources in the EU in 2021, in TWh[1]



70% of the heat consumed in the EU is produced from fossil fuels in 2021

- This accounts for heat produced directly from burning fossil fuel or conversion to electricity or distributed heat

Sources: [1] CL Energy based on Eurostat data. Renewable heat includes solar, geothermal, heat pumps, biomass (including household wood consumption), UVE (Unité de Valorisation Énergétique, unit for measuring the energy produced by waste incineration), biogas and biofuels excluding transport.
**Centralised heat and electricity generation exclude renewable shares*

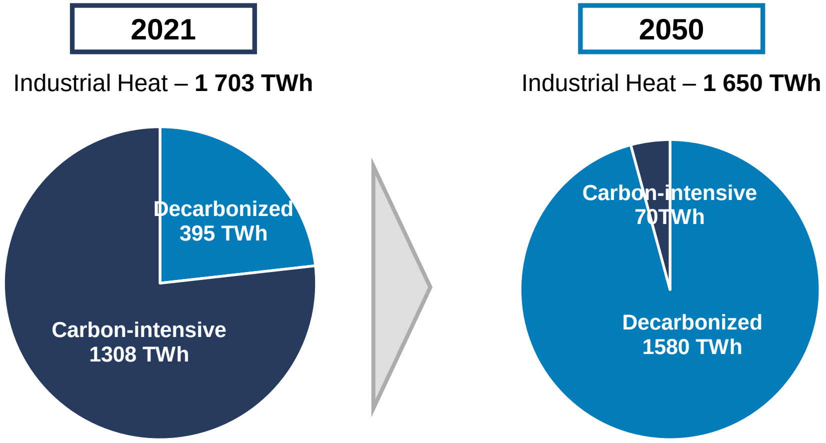
Focus on industrial heat - Decarbonised heat can complement electrification

To date, around 75% of industrial heating needs are covered by carbon-intensive sources.

In 2021, industrial processes mainly used carbon-intensive heat

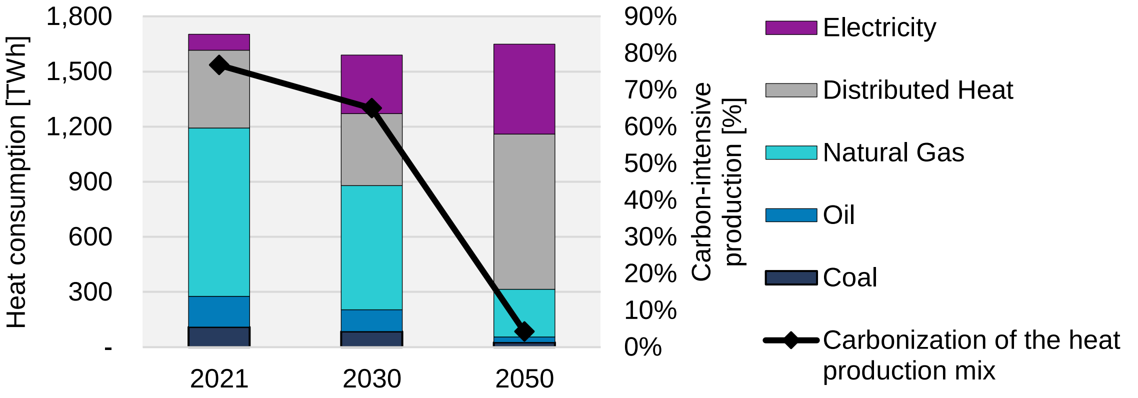
- **In 2021**, only **23% of the 1 703 TWh of heat** consumed by industry was decarbonized.
- **By 2030**, **up to 35% of industrial heat** could be **decarbonized.**[1]

Final heat production sources in EU industries in 2021 & 2050 [TWh]



- By 2050, in order to achieve decarbonisation, most of the heat in industry will need to decarbonise
- Decarbonised heat consumption will come from the following sources:
  - **Electricity from renewable and decarbonised generation** (such as wind, solar, nuclear)
  - **Heat produced from decarbonised sources** (such as geothermal, biogas, SMRs)
  - **Fossil fuel burning with CCS**

Heat consumption and carbon intensity of the heat mix for industry



 Sources: TYNDP 2024, CL analysis based on Eurostat data.

Industrial sectors with heating needs compatible with SMR

These industries have heat requirements compatible (from below 200°C to around 1000 °C) with the heat output of a SMR designed to recover part of its thermal energy, with industrial clusters also offering complementary opportunities.

Industrial parks

- Average heat consumption of a large park**: 0.8 TWh/year** [1]
- **Process**: any geographically concentrated basic heat requirement of sufficient volume, requiring a temperature <250°C
- **Creation of "competitiveness clusters"** to encourage innovation and synergies in key sectors.
- **Heat demand estimated to be relatively stable** between now and 2050 at around 288 TWh/year

Chemical industry

- Average heat consumption of a large site: **~3 TWh/year** [5]
- **Processes**: Distillation, chemical reactions and heat transfer.
- The challenge: Decarbonizing high-temperature processes, with a focus on electrification and hydrogen, as well as reducing reliance on fossil fuels, much like the challenges faced in the paper and pulp sector.
- **Heat demand estimated to be relatively stable** between now and 2050 at around 338 TWh/year

Paper and pulp

- Average heat consumption of a large site: **0.3 - 0.6 TWh/year**[2]
- **Processes:** washing, drying, bleaching, de-inking, causticizing, evaporation
- Supplement/ **replace biomass** to direct its dvpt. towards non-substitutable uses (e.g. production of synthetic fuels).
- **Heat demand estimated to be relatively stable** between now and 2050 at around 218 TWh/year

Metals industry

- Average heat consumption of a large park: **5 TWh/year** [3]
- **Processes**: Smelting, refining, casting, annealing
- Transitioning from carbon-intensive processes, such as blast furnaces, to low-emission alternatives like Electric Arc Furnaces and H2-based technologies.
- **Heat demand estimated to be relatively stable** between now and 2050 at around 79 TWh/year*

Non-metallic mineral industry

- Average heat consumption of a large park**: 3,5 TWh/year** [4]
- **Processes**: Kilning, calcination, moulding, glass forming
- The challenge is to reduce the high energy demand of kilns through the integration of alternative fuels, and adopt carbon capture technologies to meet stringent emissions targets
- **Heat demand estimated to be relatively stable** between now and 2050 at around 86 TWh/year*

Food industry

- Average heat consumption of a large site: **0.9 TWh/year**[2]
- **Process:** transformation by dissolution
- The challenge is to **improve the efficiency** of processes and manage energy requirements focused on the autumn-winter season.
- **Heat demand estimated to be relatively stable** between now and 2050 at around 202 TWh/year

Total 2050 projected heat demand for focus industries: 1211 TWh

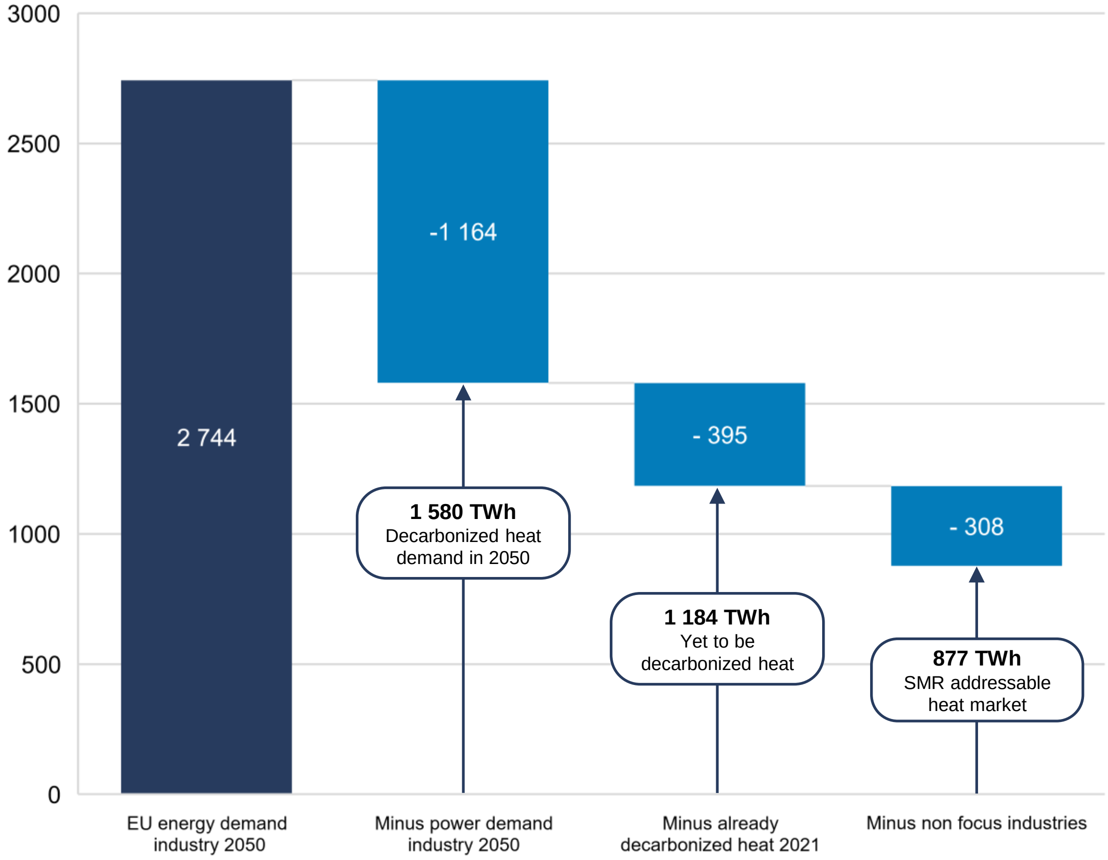
*Heat <1000°C, CL analysis based on ETM data

Source: [1] COPACEL [2] CL analysis based on Cristal Union, SNFS, Bodija, Y. et. al. [3] Arcelor Mittal [4] CL analysis based on Cembureau, Heidelberg Materials [5] Idaho National Laboratory.

The important need for decarbonization in the industrial heat sector generates opportunities for SMRs

There is a sizeable addressable market for SMRs with industrial heat decarbonisation

SMR addressable heat market (EU, 2050, TWh)



- **Suitable industries are assumed to be those with high needs for temperature <1 000°C and particularly below 500°C**
  - Food industry
  - Paper and pulp industry
  - Small to medium industries aggregated in industrial hubs
  - Some of the processes used for metallurgy and non-metallic mineral products
- **The addressable heat market is defined as the share of 2050 heat demand for suitable industries that is not already decarbonised.**
  - Overall, the industrial sector represents a decarbonized heat demand of 1 580 TWh/year in 2050, minus 395 TWh/year already decarbonized in 2021.
  - With a focus on relevant industries (heat <1 000°C), 877 TWh remain in the scope of the study.
- **Assuming that SMR will likely be used as co-generating units, the 877 TWh would be equivalent to c133 GW of SMR units**
  - The capacity expressed in GW is a thermal output and assume a capacity factor of 80%
  - Large nuclear plants could also procure heat for the same applications, as it is already the case in some industrial clusters.

 Source: CL analysis

However, SMRs will compete with a range other technologies to decarbonise heat in the identified industries

Electro-intensive technologies

Heat Pumps

- Transfer heat from a cooler space to a warmer space using a refrigeration cycle
- Space heating, food processing, and chemical industry
- Represents around 5% of the industrial electric heat used in the EU, significant potential for growth due to energy efficiency goals.
- Temperature Range: Up to 200°C.

Resistive Heating

- Generates heat by passing an electric current through a resistive element, such as a metal wire or ceramic.
- Mostly used in the production of textiles, chemicals, and metals.
- Accounts for approximately 35% of the industrial electric heat in the EU.
- Temperature Range: Up to 1300°C.

Dielectric Heating

- Heat non-conductive materials using alternating electric fields.
- Frequently used in industries for heating plastics, wood, and food processing, where precise and uniform heating is required.
- Represents about 12% of the industrial electric heat in the EU.
- Temperature Range: Up to 300°C.

Microwave & Infrared Heating

- Use of radiations to heat the material.
- Frequently used for drying, cooking, and sterilizing, particularly in the food industry, or heating surfaces in industries such as textile or manufacturing
- Represents about 12% of the industrial electric heat in the EU.
- Temperature Range: Up to 300°C for MW & 500°C for Infrared.

Non-electric-intensive technologies

Natural Gas CCS

- Burning natural gas, while capturing the produced CO2 using CCS technology.
- Used in industries such as cement, steel, and chemical manufacturing.
- Represents around 30% of the industrial non-electric heat used in the EU, slight decrease to come due to the rise pf more sustainable alternatives
- Temperature Range: Higher than 1000°C.

Solid biomass

- Burning organic materials such as wood pellets, agricultural residues, and other bio-based materials.
- Suitable for various industries, e.g. food processing, paper manufacturing, or district heating.
- Represents about 20% of non-electric industrial heat production in the EU.
- Temperature range: Higher than 1000°C.

Biogas & RNG

- Burning RNG* or Biogas, which have a lower environmental footprint as NG.
- Same use and applications as Natural Gas
- Represents ~10% of industrial non-electric heat in the EU, expected to grow to around 25% by 2050.
- Temperature Range: Higher than 1000°C.

Hydrogen (H2)

- Hydrogen can be used as a clean fuel source, producing heat through combustion without emitting CO2. Green hydrogen, produced via electrolysis using renewable energy, is particularly promising.
- Possibility to use H2 across a wide range of temperatures & for various industrial processes.
- Currently around 2% of non-electric industrial heat production in EU, with a significant growth expected, up to 20% by 2050 as H2 infrastructure develops.

Note: RNG: Renewable Natural Gas

Source: CL analysis, Ambienta Industrial Investment

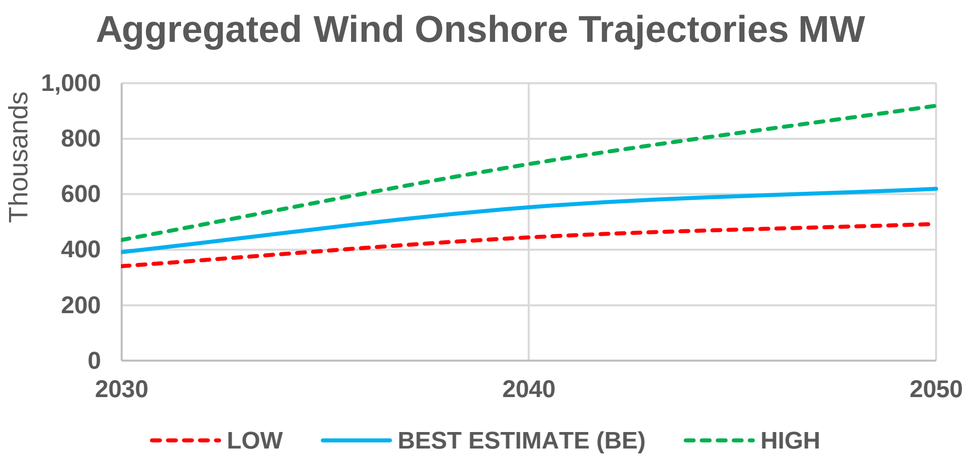
8.

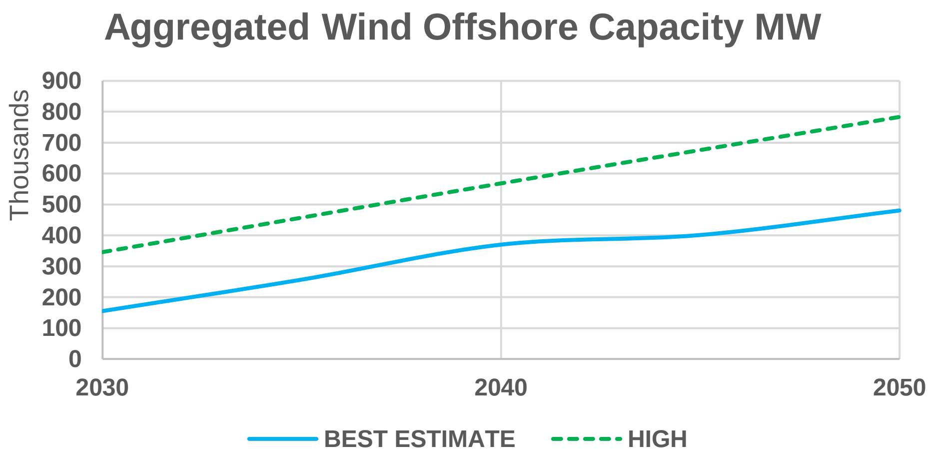
Annex – Details on modelling assumptions

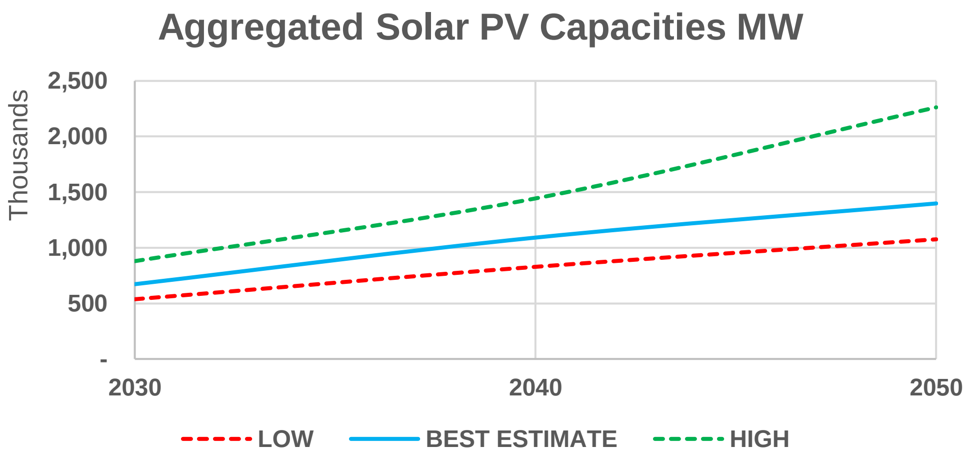
RES capacities can be endogenously expanded within the model based on ENTSOE Draft TYNDP 2024 RES potential

Within the TYNDP 2024, ENTSOE has defined RES potential for each of the technologies based on external studies.

Note from ENTSOE TYNDP supply input workbook:
The upper range has been built independently for each country by taking the maximum across a set of published study. The resulting EU aggregated level is therefore higher than in any particular study.





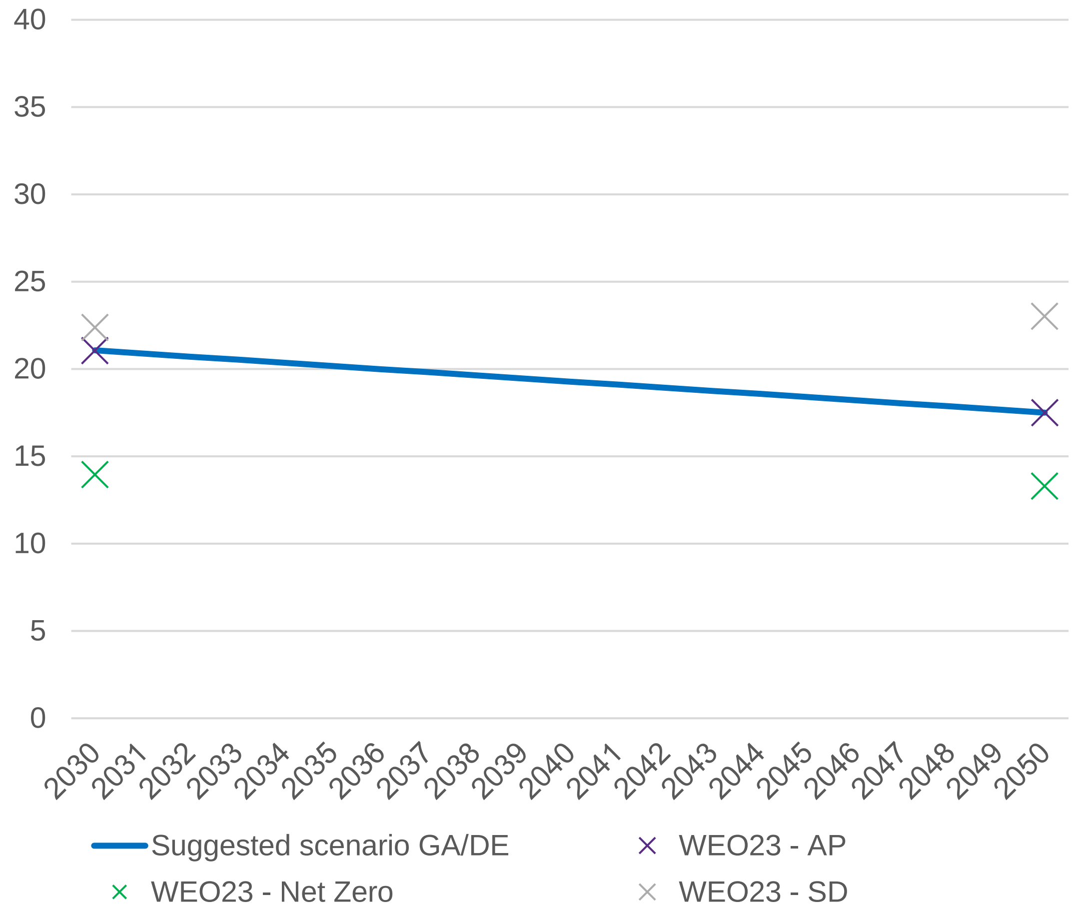


 Source: ENTSOE TYNDP 2024

The gas price outlook is based on IEA's World Energy Outlook latest update

- **Across all scenarios**, gas prices are converging towards the WEO23 Announced Pledges scenario.
- The latest update of the World Energy Outlook (WEO23) projects a lower gas price than previously mainly due to the strengthening of dollar compared to euro.
- Moreover, gas used in the power sector will progressively integrate green gases (biogas, hydrogen from electrolysis, e-methane). While the blended price of gas is projected to increase because of the higher price of green gases compared to natural gas, the associated ETS carbon content is projected to decrease.

Gas price outlook (€/MWh, real 2022)

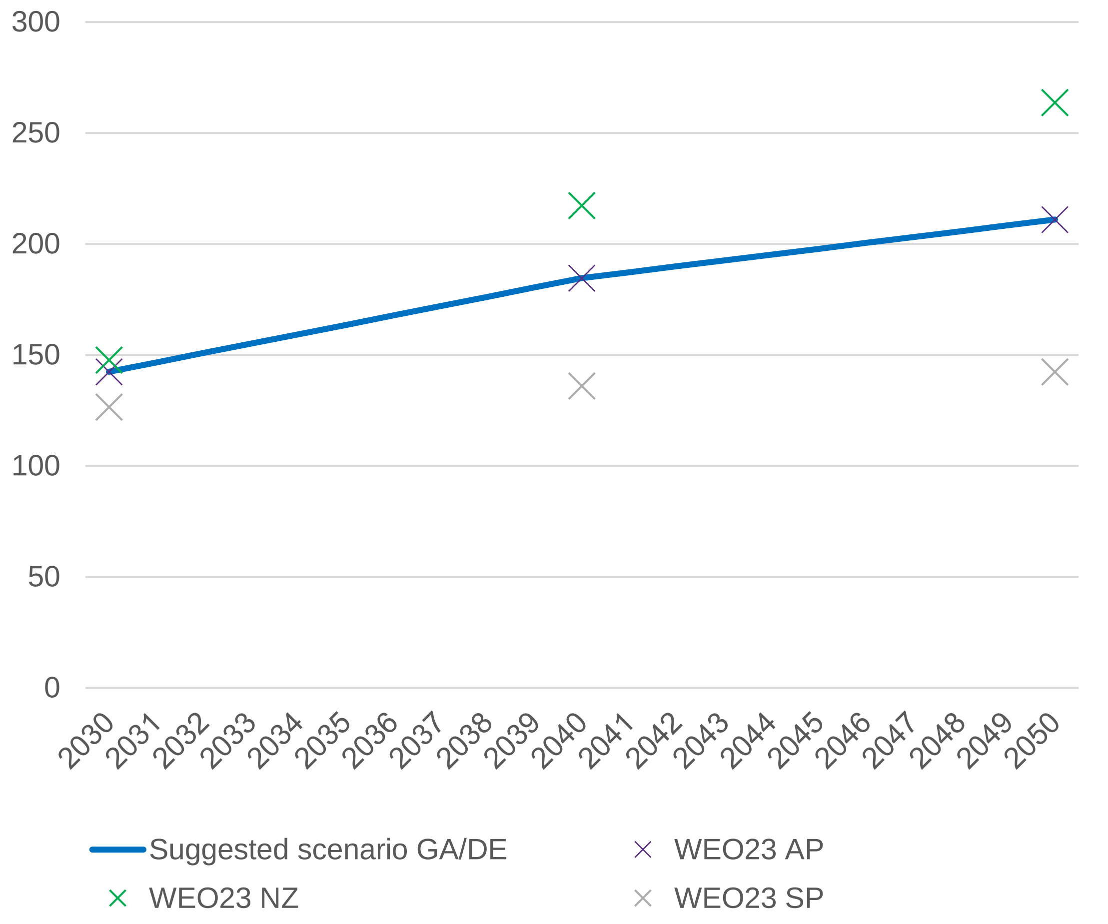


 Source: IEA World Energy Outlook 2023

The CO2 price outlook is based on IEA's World Energy Outlook latest update

- **Across all scenarios**, CO2 prices are converging towards the WEO23 Announced Pledges scenario.
- The latest update of the World Energy Outlook (WEO23) projects a lower CO_2 price than previously mainly due to the strengthening of dollar compared to euro.

CO2 EU ETS price outlook (€/t, real 2022)



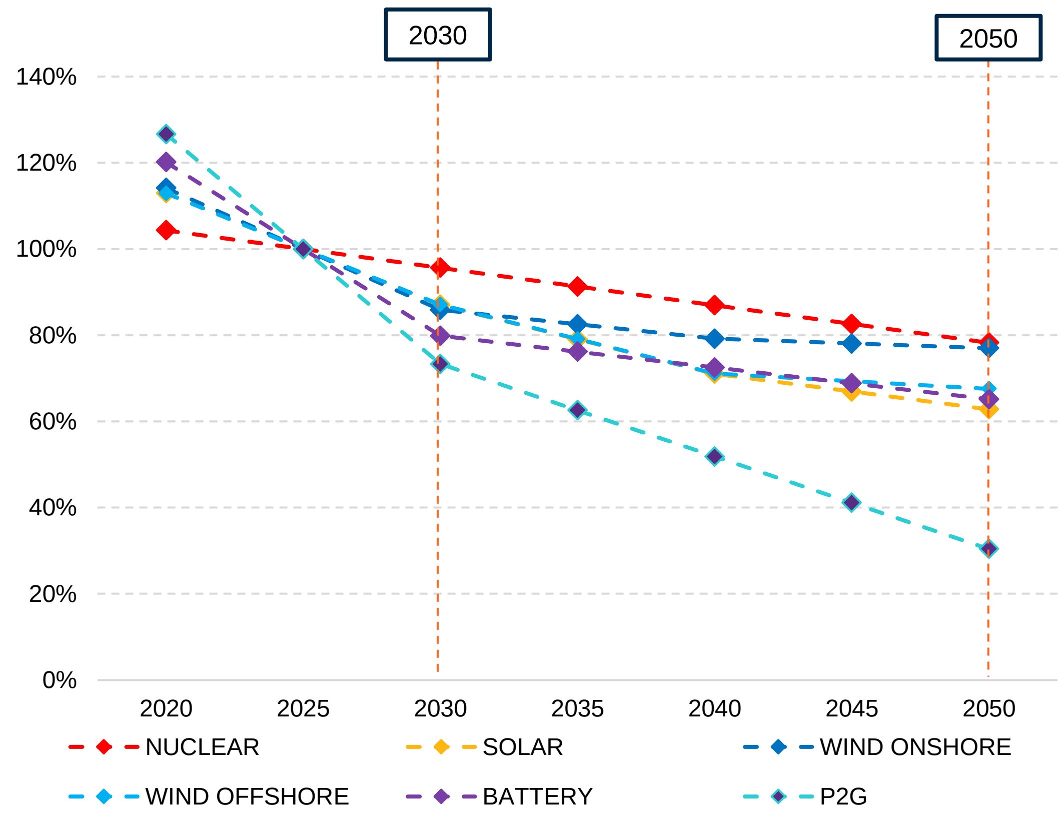
 Source: IEA World Energy Outlook 2023

Renewable technologies and storage technologies CAPEX outlooks project a steep learning curve based on EC projections

- In the process of designing the new 2050 energy roadmap, the European Commission has published a market wide review of technology cost outlook in February 2024 ("Technology Pathways") to ensure the robustness and representativeness of the current projects.
- This publication accompanied the publication of the impact assessment report for EU 2040 climate target

% reduction compared to 2025	2030	2050
Nuclear	-4%	-22%
Wind onshore	-13%	-37%
Wind offshore	-14%	-23%
Solar PV	-13%	-32%
Power to gas	-20%	-35%
Battery	-27%	-70%

RES and storage cost reduction (% from 2025)

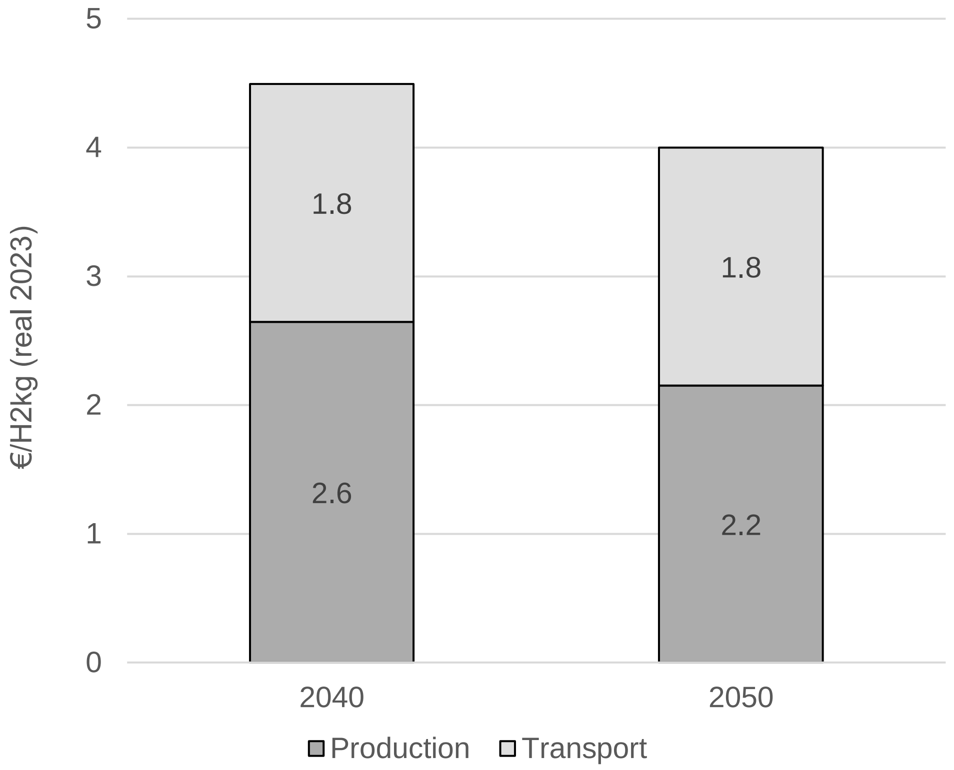


 Source: CL analysis, EC Technology Pathways 2024

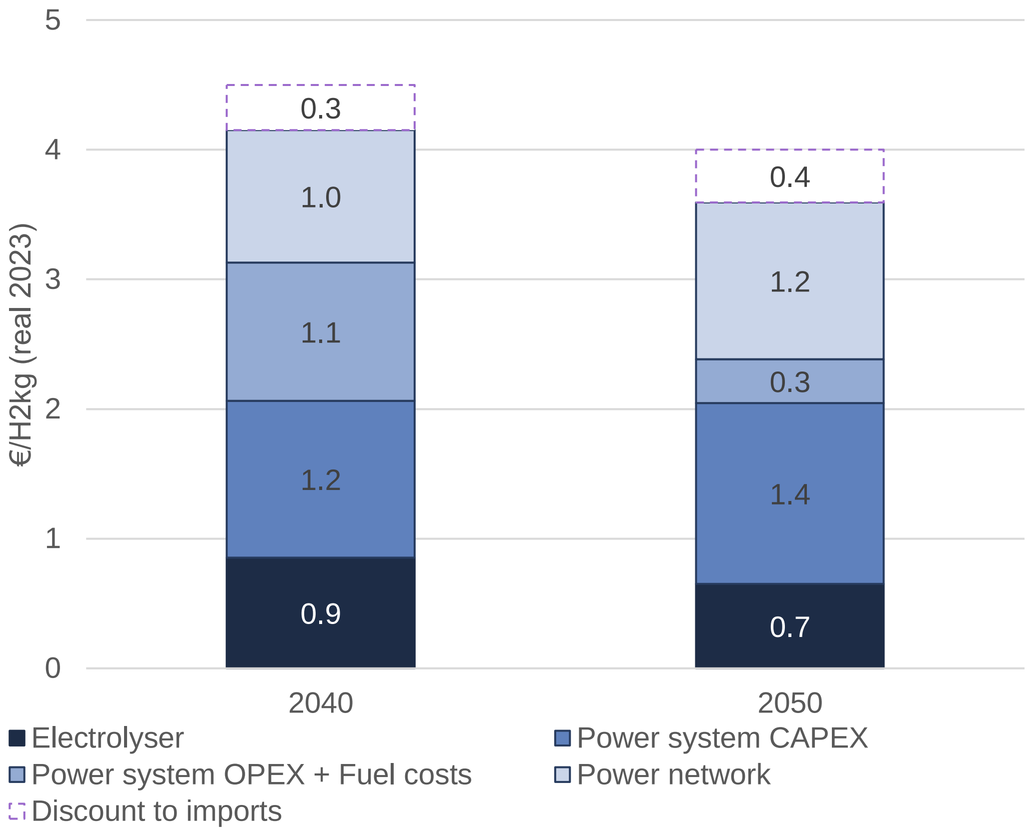
External sources are used to project H2 import and production cost

The cost of producing H2 through electrolysis in the EU is projected to be lower than importing it, leading to overall benefits

Marginal H2 import cost



Marginal H2 EU production cost [1]



Source: CL Energy analysis based on total planned export costs in RMI's "The Value of Green Hydrogen Trade for Europe", and IEA's "Global Hydrogen Review 2023"

Note: 1) The marginal cost of producing hydrogen in the EU is calculated as the total additional system cost of producing the difference in H2 demand between the "electricity system and the "energy system" approach. Both marginal costs are assumed to describe the market prices

Transmission and distribution network costs and system balancing costs are assessed based on a thorough literature review

The assessment of the three scenarios on security, economic and sustainability criteria derived from outputs of the European power market modelling was complemented with quantitative assessment of indirect costs Transmission & Distribution grid development and Ancillary services and grid stability cost.

Key driver	Description	Sources
Criteria		
Additional Transmission and distribution network costs	How would the need for additional infrastructure (e.g. gas and power transmission) evolve on EU and national levels?	■ National Grid, Pathway to 2030 (2023) ■ REE, Plan de Desarrollo (2020) ■ Tennet, Investeringsplannen - Net op Land & Zee (2023) ■ RTE Futurs Energétiques 2050 (2022) ■ RTE, schema décennal de développement du reseau (2019) ■ NEA, Full Costs of Electricity Provision (2018) ■ AGORA (2015), Delarue et al. (2016), KEMA (2014)
Ancillary services and grid stability	What would be the need for Ancillary services in future power systems and how can nuclear contribute to ensuring network stability?	■ National Grid, Pathway to 2030 (2023) ■ REE, Plan de Desarrollo (2020) ■ Tennet, Investeringsplannen - Net op Land & Zee (2023) ■ RTE Futurs Energétiques 2050 (2022) ■ RTE, schema décennal de développement du reseau (2019) ■ NEA, The Full Costs of Electricity Provision (2018) ■ Delarue et al. (2016) ■ AGORA (2015), Hirth et al. (2013 & 2015), Holttinen et al. (2011 & 2013)

 Source: CL analysis

Locations

Europe

Berlin
Brussels
Copenhagen
Düsseldorf
Helsinki
London
Madrid
Milan
Paris

North America

Boston
Chicago
Houston
Los Angeles
Miami
New York
Oakland
Washington, DC

Latin America

Buenos Aires
Santiago

Asia Pacific

Beijing
Singapore

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