A study for FORATOM

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

Presented to:

15 June 2021

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FTI Consulting at a glance

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FACTS AND FIGURES

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3 Nobel laureates

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AMCF Association of Management Consulting Firms

2012 award for corporate strategy

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$2 BLN
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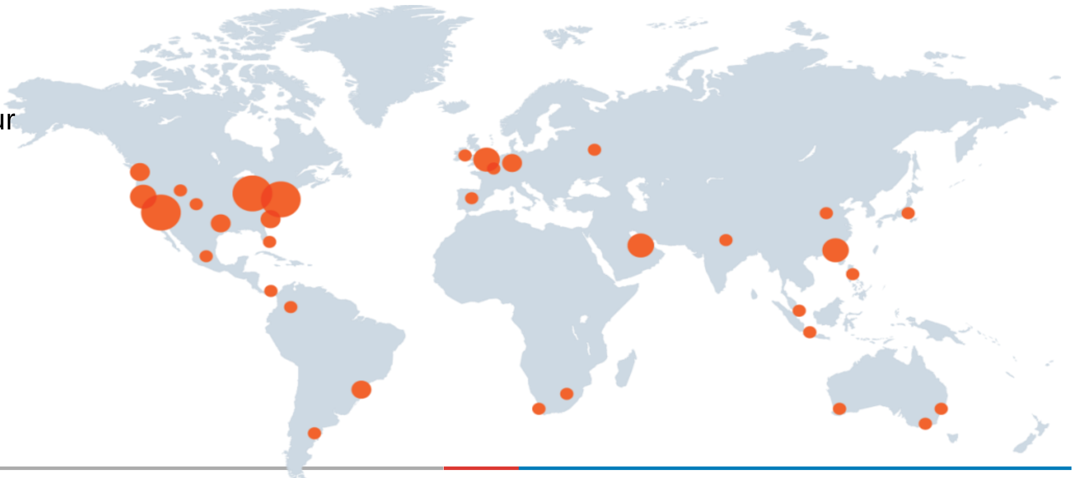
FCN
Publicly traded – NYSE



OUR EXPERTISE IN THE POWER SECTOR

Compass Lexecon has deep expertise in the regulation of the energy sector, having worked with many regulators and regulated entities in the power industry

Selection of CL clients in the power industry

Networks and systems | Wind | Solar | Storage | Hydro, Wave & Tidal | EVs

Study context and objectives

COMPASS LEXECON

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

Policy objectives	Key research questions
Decarbonisation and sustainability	Can a EU scenario with a fully decarbonized electricity mix be **credible, secure and cost efficient** without a significant share of nuclear?
Security of supply	What is the role that nuclear can play in a EU decarbonisation scenario with **growing power demand driven by strong electrification** of the economy?
Affordability /competitiveness	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 **two different scenarios** to achieving European energy policy objectives of security of supply, decarbonisation and sustainability, and affordability / competitiveness.

We assess the two FORATOM scenarios for nuclear in Europe using a multi criteria analysis based on modelling and a literature review

Two nuclear scenarios 2020-2050

- **Low scenario**
- **High scenario**

Impact assessment based on multi criteria analysis

European Power Market Dispatch Model

- Capacity requirements and security of supply
- Annual, daily and hourly generation outlook
- Storage requirements and curtailed energy
- Nuclear capacity factor
- Fossil fuel consumption
- CO_2 emissions
- Power prices
- Customer cost
- Investment cost

Literature review

- Job impact
- Transmission and Distribution cost
- Balancing cost
- Land use
- SO_2 emission
- NO_x emission
- Particular Matter emission

Key findings and policy recommendations

Scenario definition

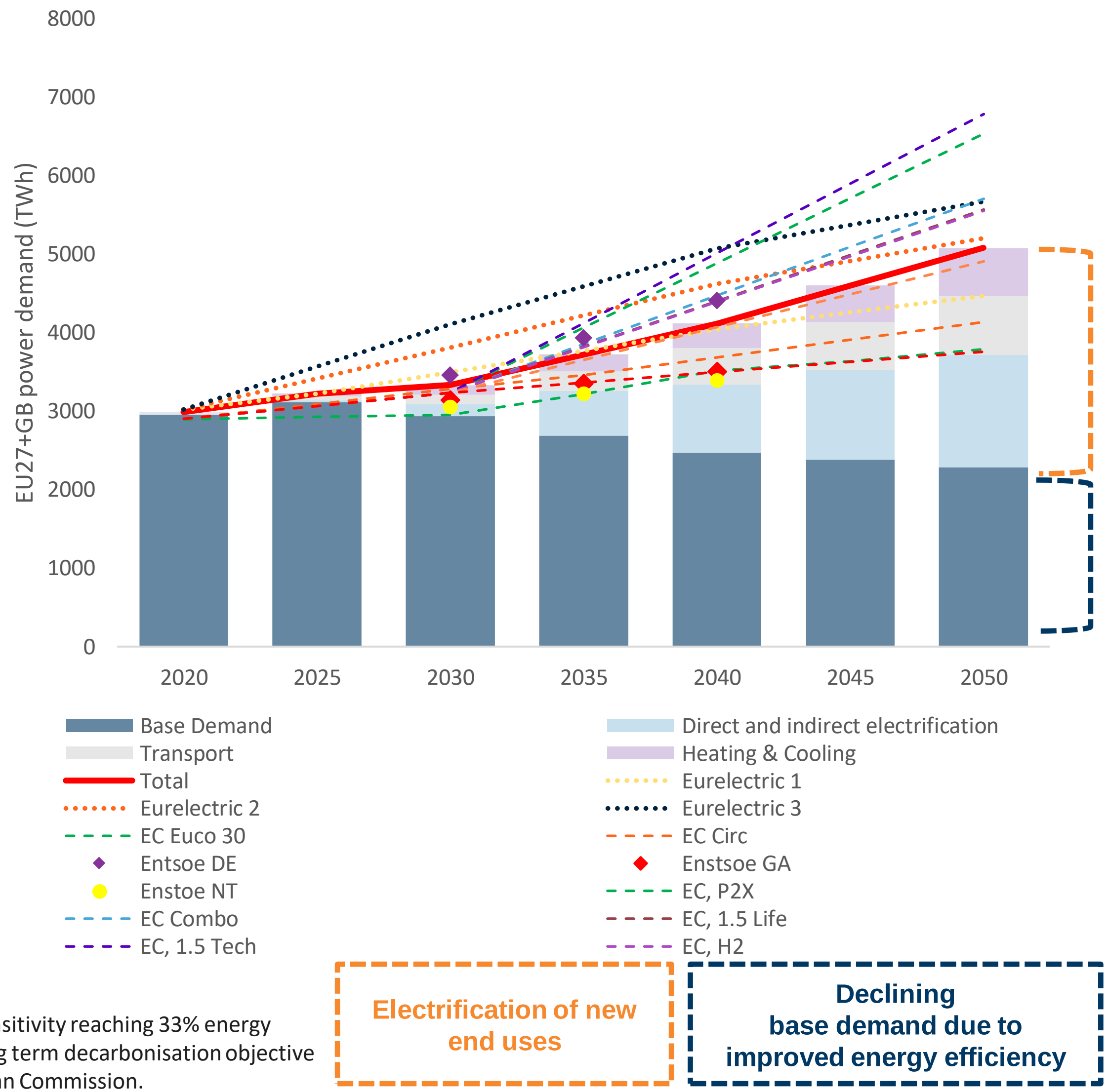
Power demand outlook captures effect of energy efficiency policies as well as electrification of end uses, in line with EC objectives

Power demand outlook to 2050

- The study models the impact and costs associated to different nuclear scenarios in the European Union, including new build, long-term operation (LTO) and phase-out to varying degrees.
- The study assumes across all scenarios:
  - **Decarbonisation** of the energy mix in 2050, compared to 1990;
  - **Further electrification** of the European economy: 2050 demand forecast is projected to reach c5000TWh
- The study also assumes technology improvements based on the European Commission reference assumptions on electricity technology costs and performances*

- The study leverages FTI-CL Energy's European power market model to dynamically simulate the impact and costs of the three different scenarios, based on a two-step optimisation process:
  - **Dynamic optimisation of the generation mix** based on the economics of RES, thermal plants and storage, to ensure security of supply and meet EC objectives at the least cost; and
  - **Short term optimisation of dispatch** of the different units on an hourly basis.

FORATOM's vision demand outlook compared to benchmarks



* EUCO33 outlook is the PRIMES sensitivity reaching 33% energy efficiency reduction in 2030 and long term decarbonisation objective developed by E3M with the European Commission.

Source: CL Energy, Eurelectric, European Commission

New end-uses of electricity are assumed to provide additional flexibility to the power system

Power demand modelled flexibility

DSR

- DSR can be activated 40 hours per year

Electric vehicles

- In addition to day/night optimisation, 25% of the vehicles are capable of optimising their load in response to the market price, making possible the modulation of consumption over about ten hours.

Heat pump and cooling

- In addition to day/night optimisation, 50% of the heat pumps are dynamically controlled in response to the market price, making possible the modulate of consumption over 2-3 hours.

Direct Electrification industry

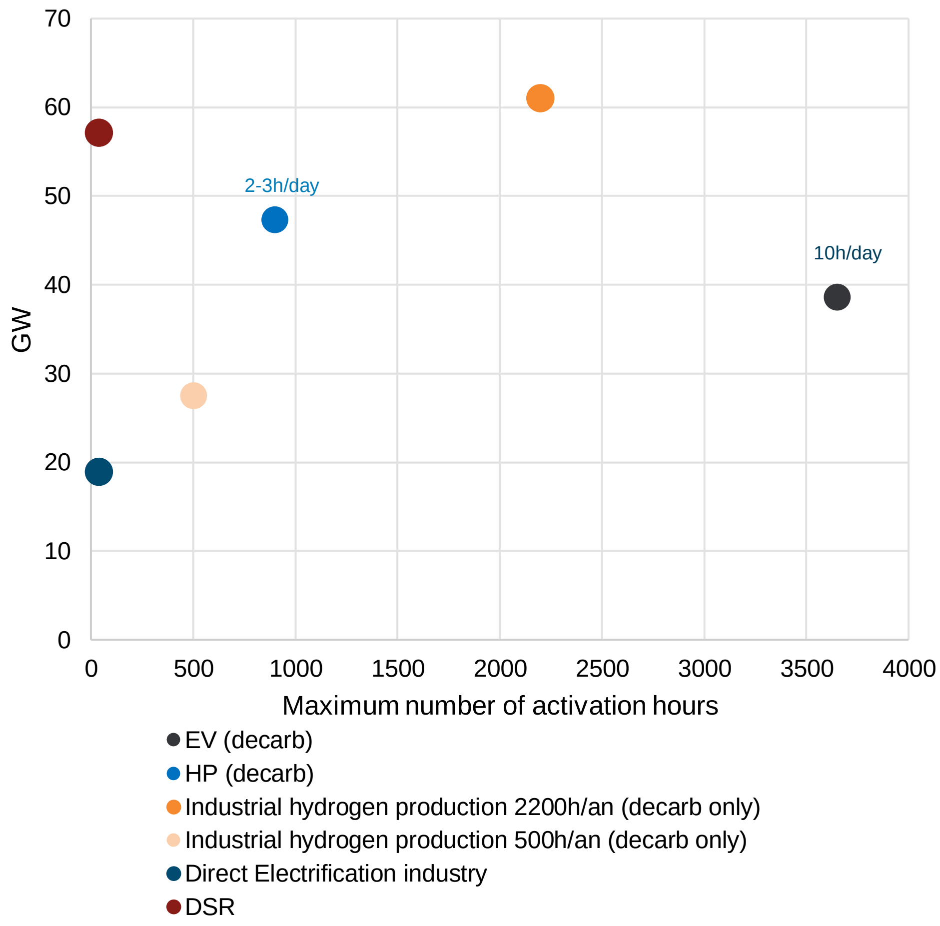
- New industrial electricity demand can be reduced 40 hours per year at 60% of its power

Industrial hydrogen production

To reflect the future potential for flexibility provided by hydrogen production for industry:

- 50% of industrial hydrogen production can be reduced 500 hours per year at 60% of its power.
- 50% of industrial hydrogen production can be stopped 2200h per year

Capacity of demand flexibility in Europe - 2050



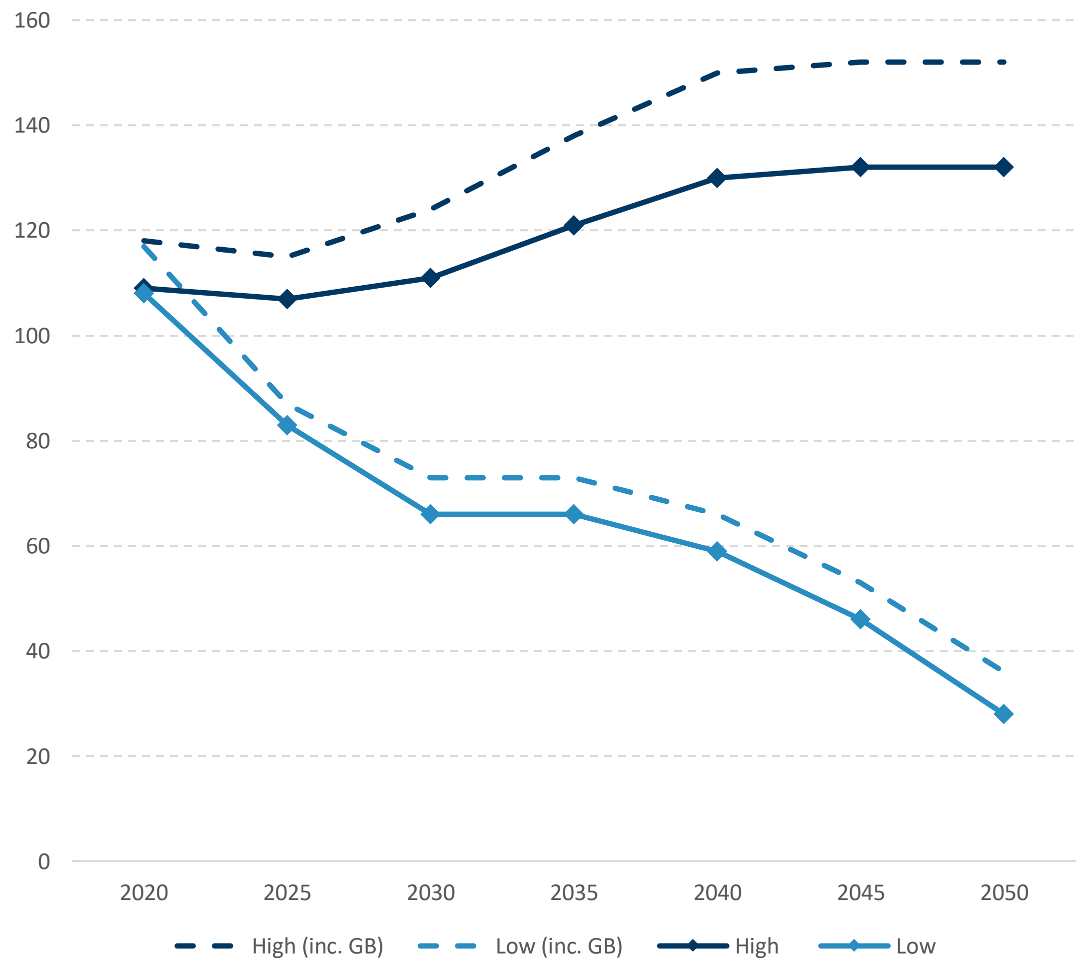
FORATOM's scenarios for nuclear in Europe reflect different assumptions for retirements, life extensions and new build

FORATOM's scenario design

- **Both scenarios are based on**
  - current nuclear plants
  - projects under construction, and
  - planed nuclear phase-down policies.
  - Each scenario then assumes different life extension decisions as well as different commissioning date for future new nuclear plants.
- **In the short term, in both scenarios, nuclear capacity drops by 2 to 25 GW by 2025**

- **In the longer-term, variation of extension and new built decisions lead to the following scenarios:**
  - In **the low scenario**, most existing plants close without further life-time extension and new plants projects fail to conclude.
    The nuclear capacity decreases to **28 GW by 2050**.
  - In the **high scenario**, several long-term operation (LTO) extensions are awarded and a number of additional new plants (including c. 22 GW of SMR and <1 GW of Gen-IV) are commissioned replacing thermal baseload and contributing to decarbonisation of the power sector and wider European economy.
    The nuclear capacity reaches **132 GW by 2050**.

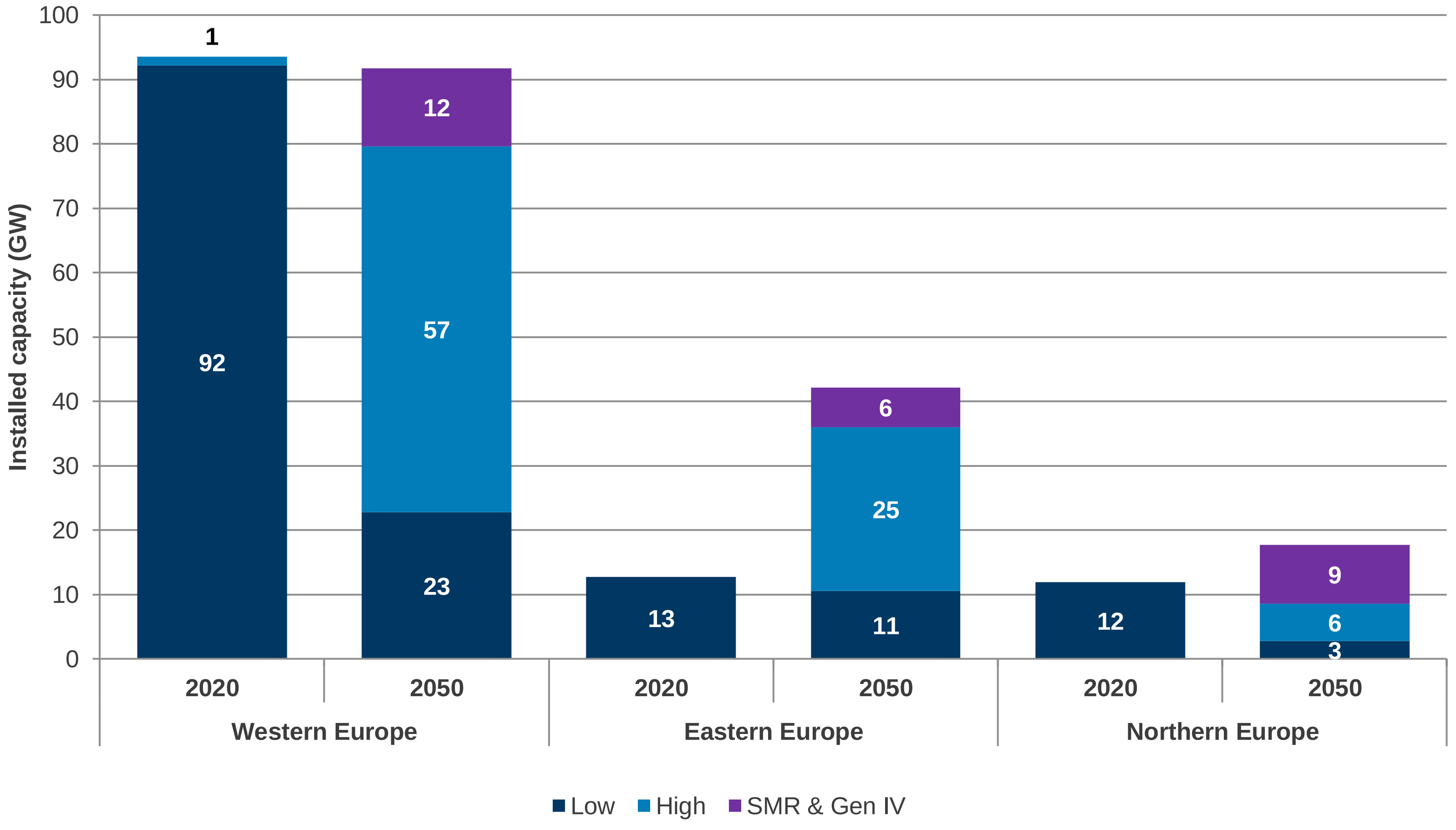
EU-28 FORATOM's nuclear installed capacity outlooks (GW)



Source: CL Energy analysis based on FORATOM inputs

FORATOM's scenarios are derived country by country and reflect different national approaches towards nuclear power

Installed nuclear capacity by region and scenario (GW)



Source: CL Energy analysis based on FORATOM inputs

Modelling results and key insights

Both scenarios see a significant increase of RES and flexible resources

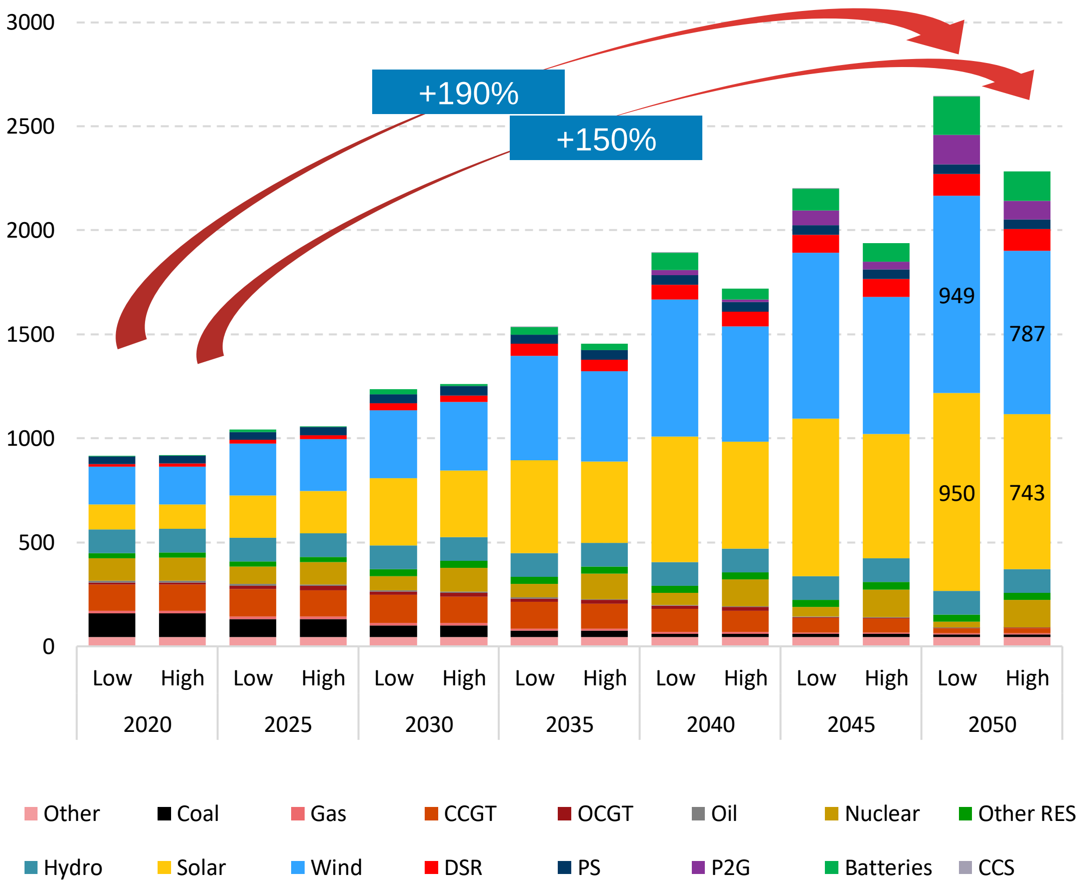
Installed capacity outlook in the Low scenario

- **In the low scenario, RES increase by 190%,** (+1610 GW of new RES) reaching a total of c. 2050 GW, including 950 GW of wind and 950 GW of solar.
- Additionally, 325 GW of new flexible capacity is installed of which 183 GW of batteries and 143 GW of Power to Gas to Power.

Installed capacity outlook in the High scenario

- **In the high scenario, RES increase by 150%,** (+1240 GW of new RES) reaching a total of c. 1680 GW, including 790 GW of wind and 750 GW of solar.
- Additionally, 230 GW of new flexible capacity is installed of which 140 GW of batteries and 90 GW of Power to Gas to Power.

Low and High scenario installed capacity outlook (GW)



Note: Other includes small distributed thermal non-renewable generation; Wind includes onshore and offshore; PS stands for “Pumped Storage”; P2G stands for “Power to Gas”

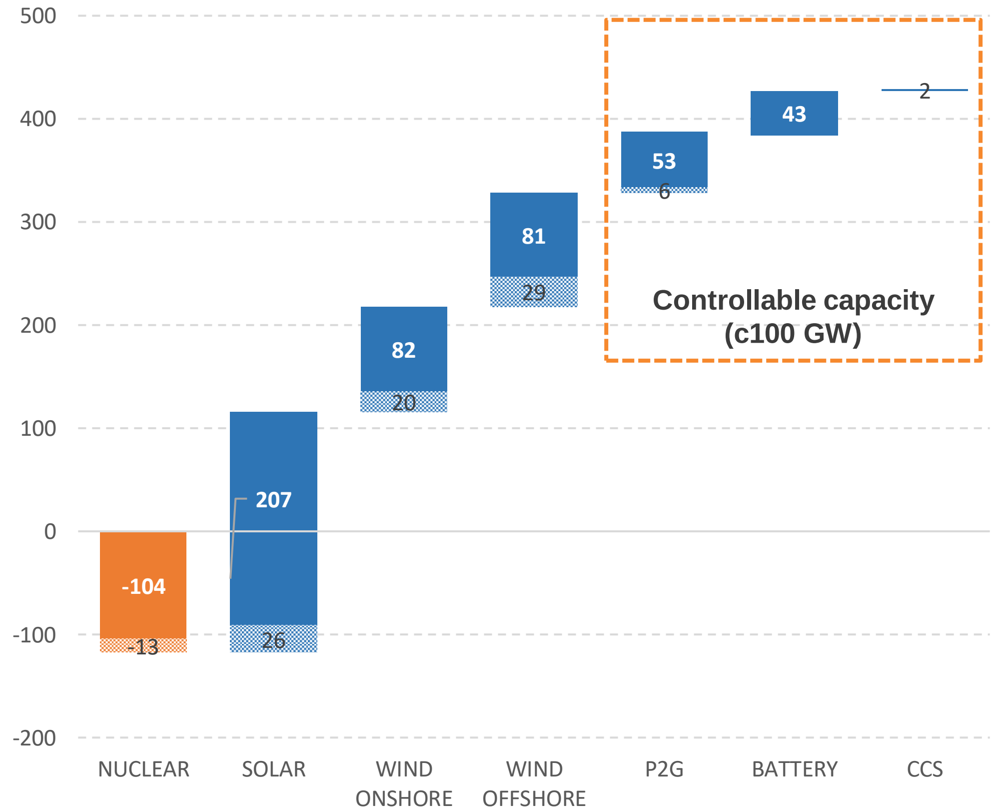
Source: CL Energy modelling

The comparison of the Low and High nuclear scenarios shows a need for a significant additional increase of RES and flexible capacity

- **The reduction of EU nuclear capacities in the Low scenario by 104 GW in 2050 would be compensated by a combination of RES capacity to fill in the generation volume gap and flexible capacity to maintain security of supply:**
  - **369 GW of variable RES capacity**
    - 207 GW of Solar capacity
    - 82 GW of Onshore Wind capacity
    - 81 GW of Offshore Wind capacity
  - **98 GW of flexible capacity**
    - 53 GW of Power to gas to power
    - 43 GW of Battery
    - 2 GW of new (CCS) thermal capacity
- In addition, given the interconnection with neighbouring countries, the reduction of nuclear capacities would also be compensated by additional variable RES and controllable capacities in interconnected power markets.

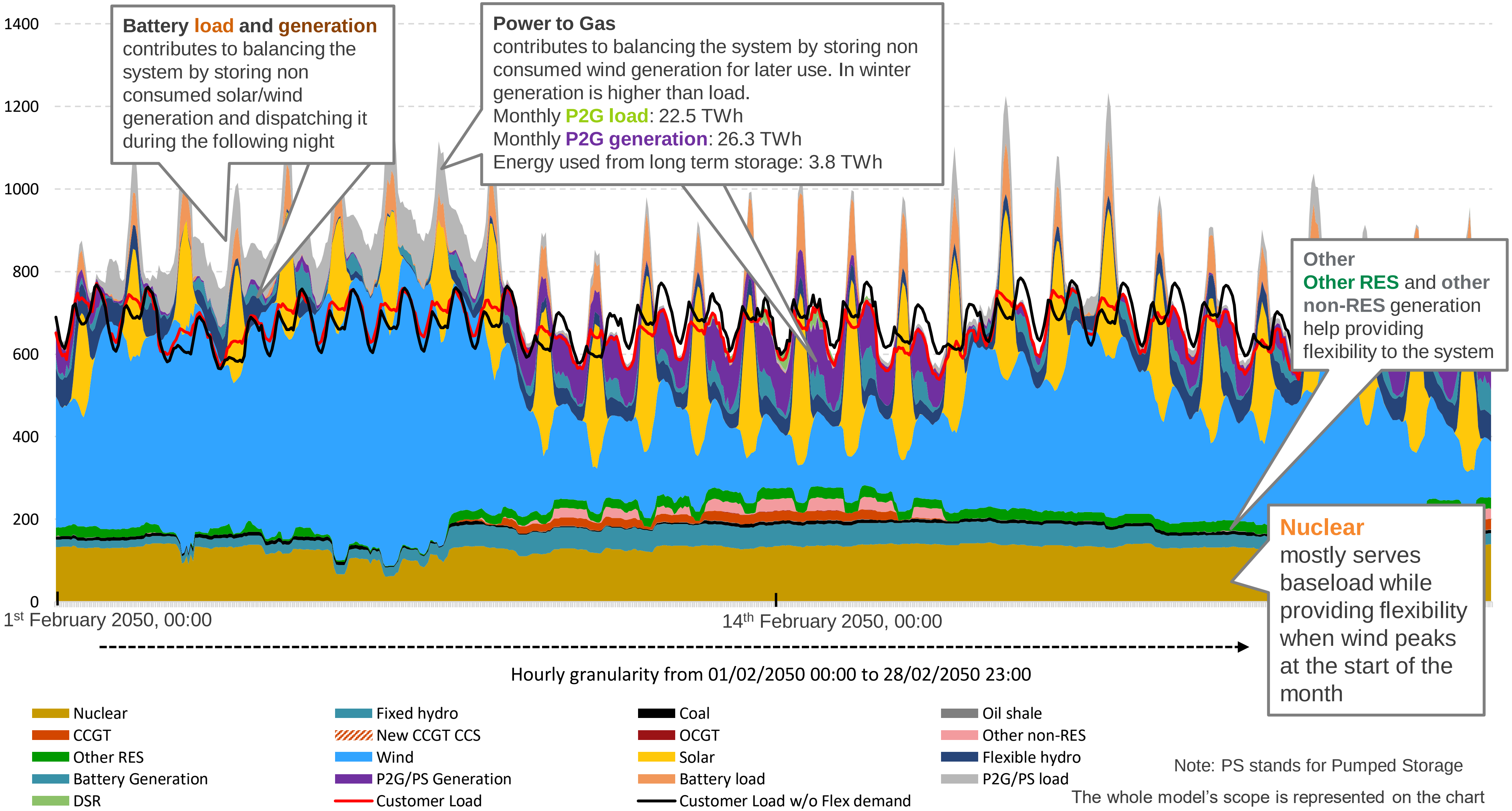
Note: the figures in the text indicate the differences between low and high scenarios on the EU-27 scope (i.e. excluding the shaded areas on the chart which present the additional changes of capacity between the low and the high scenarios for the whole model's geographic scope)

Capacity development differences by technology between the Low and High scenarios in 2050 (GW)



In winter in 2050, nuclear continues to operate baseload most of the time as excess RES production is absorbed by storage and P2G

Hourly generation mix during a winter month (MWh/h) – February 2050 High scenario



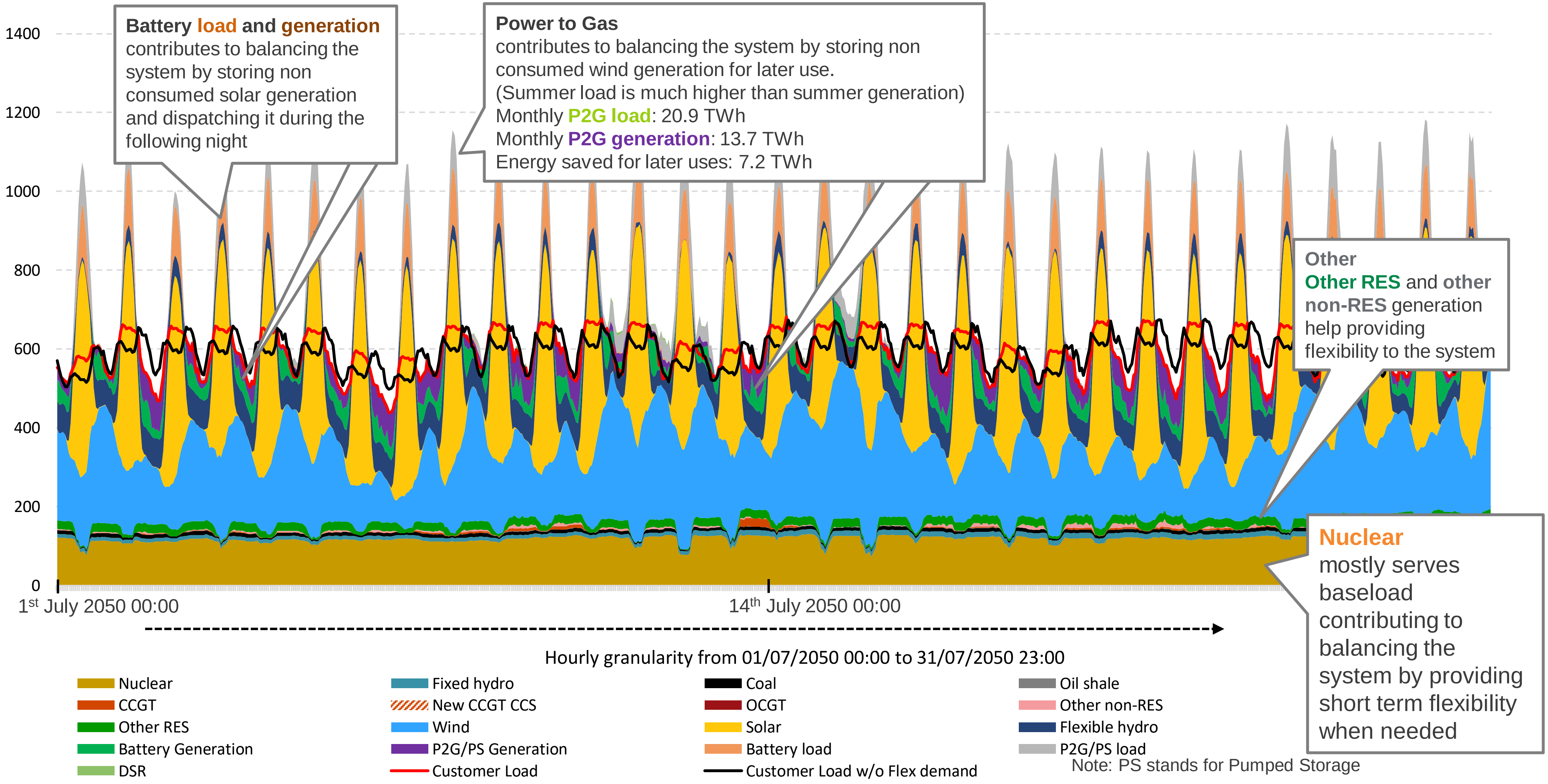
Note: PS stands for Pumped Storage

The whole model's scope is represented on the chart

Source: CL Energy modelling

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

Hourly generation mix during a summer month (MWh/h) – July 2050 High scenario



Note: PS stands for Pumped Storage

The whole model's scope is represented on the chart

Strong development of short term and long term storage will be critical to maintain an efficient and economic operation of nuclear plants

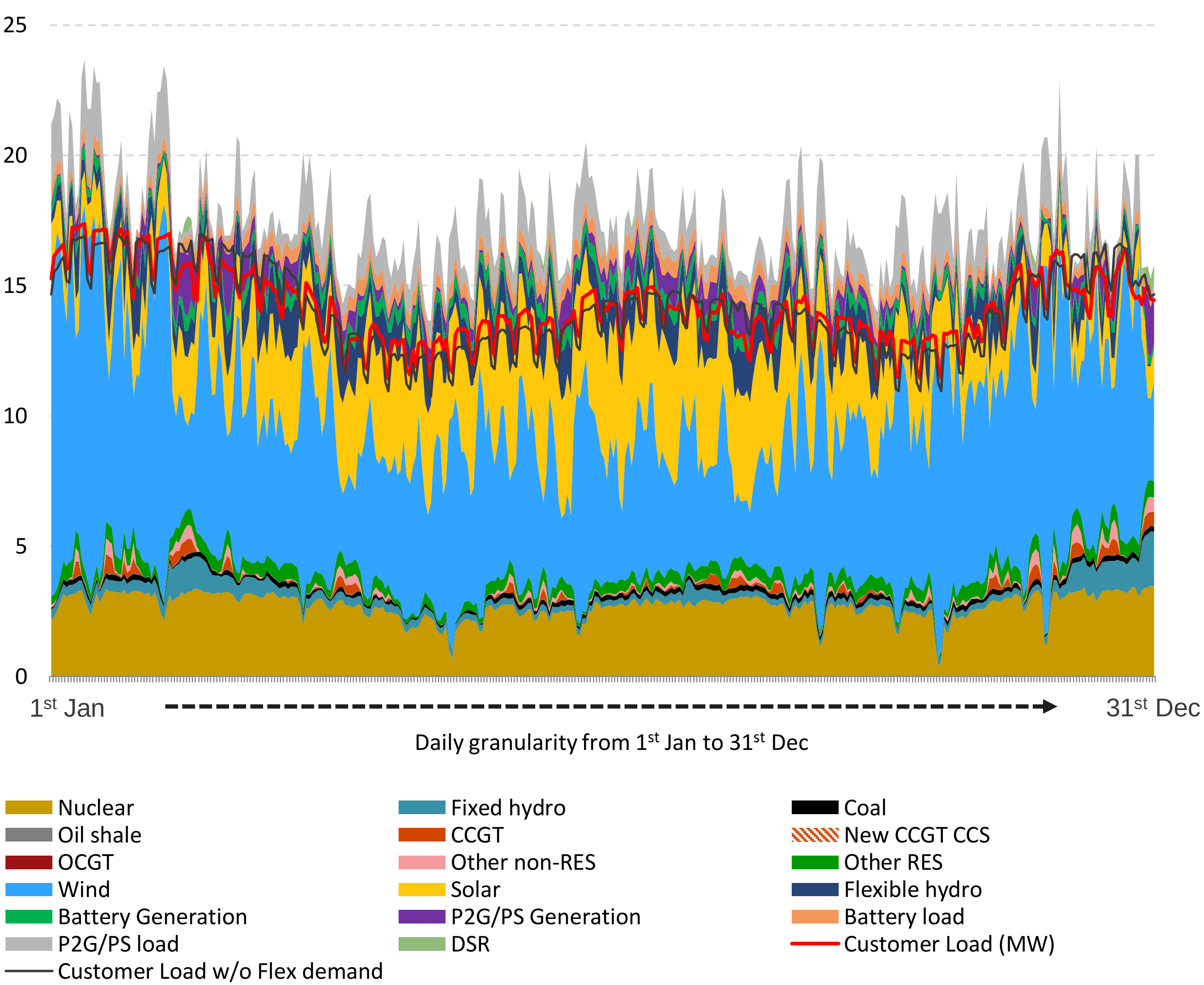
Nuclear contributes to providing flexibility and baseload power to the system by cycling at different times:

- **It can complement solar and wind variability** by providing flexible and dependable carbon free generation.

Seasonal utilisation of storage and P2G:

- **Storage capacities** are essential to stabilise the power system by capturing excessive production and generating in scarcity situations.
- **In summer**, beyond batteries transferring solar power from day to night, P2G enables solar power to be transferred from one day to the next. It can represent up to 3% of the customer load.
- **In winter**, P2G enables to offset low wind days and weeks, transferring power on a seasonal timeframe. P2G can represent up to 6% of the customer load.

Daily generation mix (TWh) – full year 2050 High scenario



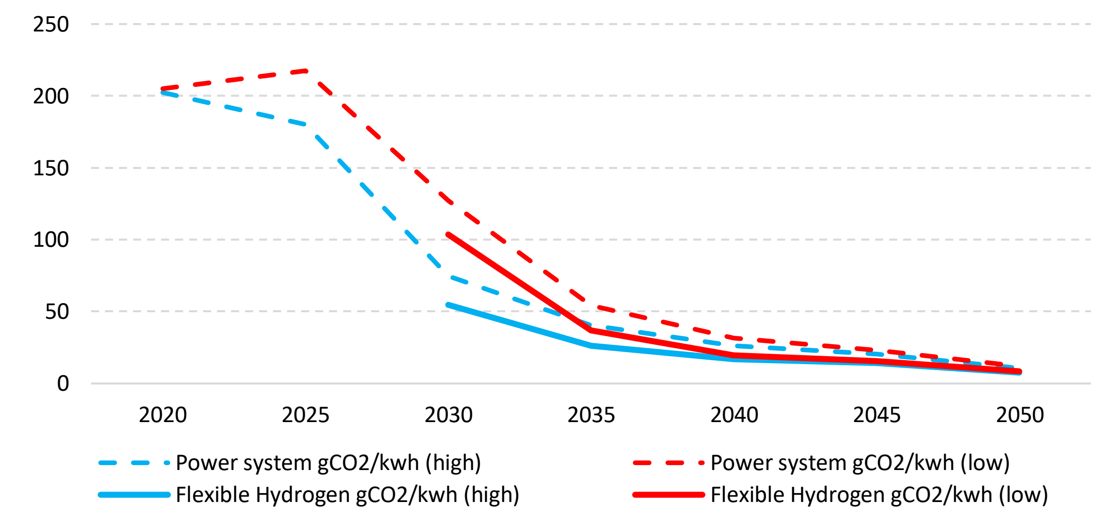
The whole model's scope is represented on the chart

Source: CL Energy modelling

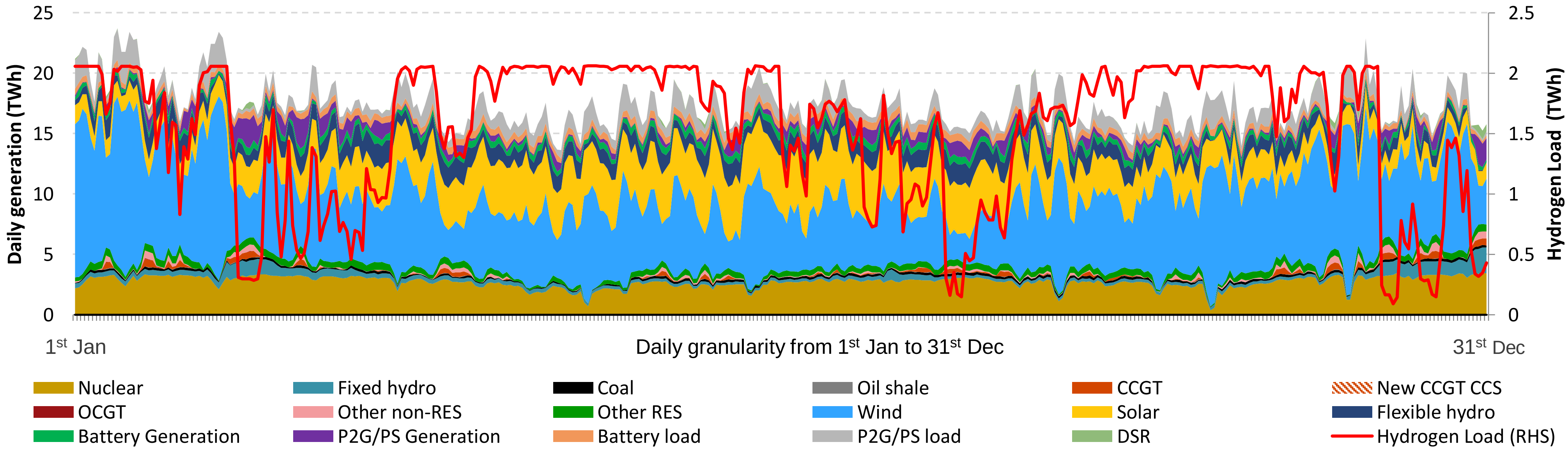
Flexible hydrogen production benefits from low marginal cost of low carbon technology generation

- **The consumption of power for flexible hydrogen production is optimized to benefit from low marginal cost low carbon generation while respecting the minimum assumed load factor of 75% of the electrolyser to recoup fixed costs:**
  - In line with the power system carbon content outlook, hydrogen production would emit less CO2 emissions in the high scenario especially between 2030 and 2040.
  - In 2050 with decarbonisation of the power system hydrogen production would come from 82% come from RES and 18% from nuclear in the high scenario

Carbon content of power by scenario (gCO2/kwh)



Daily Generation mix vs flexible hydrogen production in 2050 – High scenario



The whole model's scope is represented on the chart

Conclusion: Nuclear contributes to ensuring security of supply and the low nuclear scenario would increase a number of challenges

Reliance on yet immature storage technologies

- A low share of nuclear in the energy mix will significantly increase the power system's reliance on large scale yet immature storage technologies (reaching around 325 GW of batteries and seasonal storage such as Power2X2power in 2050 in the Low scenario)

Increased reliance on thermal generation

- By closing nuclear capacity instead of investing in its long-term operation, **2370TWh of additional fossil fuel based thermal generation will be needed** in the short to medium term, representing a **+22% increase** or the equivalent of 4 years of the EU's total power generation

Increased dependency on imported fuel

- The low nuclear scenario would **increase fossil fuel consumption** (gas and coal) **by 4150TWh**, pushing up Europe's dependence on fossil fuels to an equivalent of +26% in gas consumption and +12% in coal consumption between 2020 and 2050.

In the Low scenario, nuclear closure and limited nuclear investments would induce 1590 $MtCO_2$ of additional emissions in the short term

Anticipated nuclear closure and limited new nuclear investments in the Low scenario would materially increase total emissions over 2020-2050:

- An early closure of nuclear plants would require new thermal plants in order to ensure security of supply, as well as additional thermal generation from existing plants which would generate **1590 Mt** of additional CO_2 emissions or **19% of total CO_2 emissions from the power sector** over 2020-2050 in the low scenario.

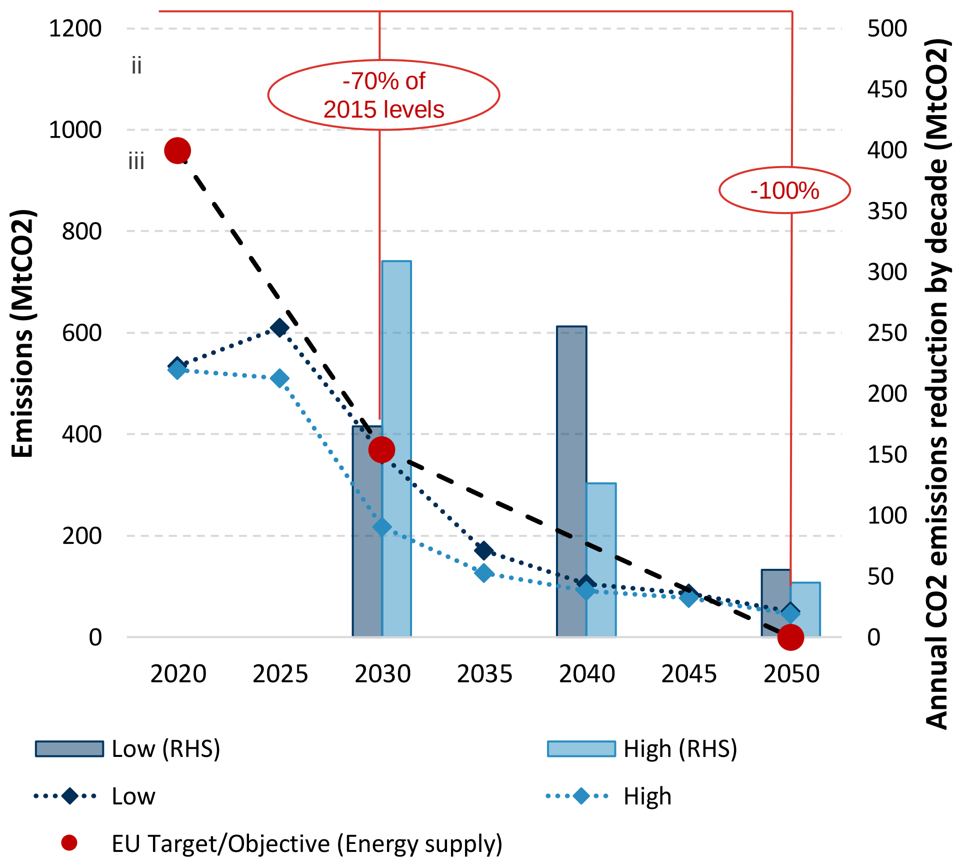
While – by construction – both scenarios achieve the CO2 emission reduction target in 2030 and the 2050 objective, maintaining nuclear energy through extensions and new investments would significantly lower the CO_2 emission impact of the power sector, thereby further strengthening the role of electricity in the transition.

Furthermore, anticipated closure of nuclear in the low scenario would lead to increased CO_2 emission by 2025, thus jeopardizing 2030 increased ambition.

Note:

i) While both scenarios use a similar EU ETS price outlook, an increase of emission (resp, decrease) would put an upward pressure (resp. downward) on EU ETS price further impacting the cost to end-customers.

CO_2 emissions outlook for the power sector



ii) The EU target 2020 for Energy supply emissions has been adapted to EU-27. To avoid corner solutions in the modelling, the 100% reduction of 2050 emitted CO2 is set slightly under this threshold.
iii) 2020 modelled CO2 emissions are much lower than the target as a result of the COVID-19 impact on power demand (-5% on average) and on thermal SRMCs, gas becoming more competitive than coal.

Nuclear contributes to ensuring environmental sustainability and the Low scenario would increase some of the challenges

Reduced CO2 emission

- Anticipated nuclear closure and limited new nuclear investments in the low scenario would materially increase total emissions over 2020-2050 (c1590MtCO_2 or +19%), especially before 2035.

Environmental footprint

Air and water

- Pollution would be reduced by c9%, including a 8% reduction in SO_2 emissions, 7% in NO_x and 12% in PM

Land use

- The amount of land needed for power generation would be about 10000km2 lower by 2050 – equivalent to 4 times the area of Luxemburg – because nuclear generation requires less land than variable RES and fossil fuels to produce the same amount of energy

Curtailed energy

- In the longer term, the closure of nuclear power plants in the low nuclear scenario with no life time extensions and limited new nuclear investments would induce about 12TWh of additional curtailed energy in 2050 compared to the high nuclear scenario (a +90% increase)

The study assumes technology improvements based on the EC reference assumptions on electricity technology costs and performances

CO2 emissions outlook from the power sector

Potential cost reductions of different technologies:

The cost associated with power sector decarbonisation will depend significantly on the future possible cost reductions of different technologies, as a result **of learning by doing and technology innovations**.

- In the process of designing the new 2050 energy roadmap, the Commission has set up a market wide review of technology cost outlook to ensure their robustness and representativeness of the current projects.
- Amongst other feedbacks received, the updated E3M technology cost outlooks reflect the latest expectation from market participants and developers of future cost reduction.

% reduction compared to 2015	2030	2050
Nuclear	25%	37%
Wind onshore	17%	31%
Wind offshore	42%	50%
Solar PV	47%	59%
Power to gas	55%	70%
Battery	64%	75%

Source: FTI-CL Energy analysis, E3M

Nuclear contributes to mitigating some of the costs associated with the power sector transition

Impact of anticipated closures and life extensions on costs

- Over the modelling horizon, nuclear life time extension and new build in the high scenario would mitigate the impact of the low carbon transition on consumer costs, by saving a total of **392bn€** (real 2019) compared to the low nuclear scenario over 2020-2050 thanks to lower total generation costs. This represents a saving of c5% of total EU consumer costs over 2020-2050.

Residual value of investments

- Given the long lifetime of nuclear assets (60 years of Gen-III nuclear power plants) the Low scenario would reduce the residual value of investments by **€942 billion in 2050** compared to the high scenario. This represents 28% of total annualised new CAPEX investment over 2020-2050. The residual value is calculated as the sum of the CAPEX annuities of operational new investments on their remaining economic lifetime after 2051.

Network and balancing costs

- Compared to anticipated nuclear closures in the Low scenario, further nuclear development in the High scenario would reduce network and balancing costs by **168bn€** (real 2019) by 2050.

Conclusions

Nuclear contributes to the transition towards a European decarbonized power system:

- **In the short to medium term**: anticipated nuclear power plant closures would make the European emission targets more challenging and uncertain as it would temporarily increase emissions and could risk locking in fossil fuel investments
- **In the longer term**: nuclear can complement variable renewable sources of energy by providing proven carbon free dependable power and flexibility to the system and reduce the system reliability on yet to be proven storage technologies.

Key enablers for a sustainable role for nuclear power in the European power system:

- **The timely development of storage technologies** and **flexible operation of nuclear** will be critical to ensure the complementarity of nuclear and variable renewables;
- **A market design that rewards the system value of dependable and flexible resources** is necessary to address the challenges the power system would face in a high variable RES penetration environment;
- **A market design that provides stable long-term investment and price signal** is necessary to mitigate risk exposure to more volatile power prices for low carbon CAPEX intensive technologies;
- **A regulatory framework that takes a whole value chain perspective - from R&D to operation -** is necessary to ensure a level playing field between low carbon technologies;
- Whilst life extension of existing nuclear plants is generally competitive against other low carbon resources, new nuclear power will need to **demonstrate significant cost reductions** to succeed in liberalized European power markets

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Appendices

A. Detailed impact assessment results

Power market modelling results

Power market modelling results

- **Objective**: The CL European power market model enables to simulate in the two scenarios for nuclear in Europe the dispatch of the power sector on a hourly basis as well as the long term investment needs to 2050. This allows to assess the contribution of nuclear to achieving European energy policy objectives of reliability, decarbonisation and cost efficiency.

- **Criteria**: Based on the optimised long-term investment decisions, the power dispatch model generates the optimal hourly dispatch while minimizing the system cost. This allows to assess the contribution of nuclear to the EC power sector decarbonisation by comparing the following criteria:
  - Installed capacity outlook
  - Annual Generation mix outlook
  - Hourly generation mix outlook
  - Daily generation mix outlook
  - Nuclear generation capacity factor outlook
  - Fossil fuel consumption
  - Power sector CO_2 emission
  - Wholesale power price
  - Customer cost and
  - Investment cost

While both scenarios meet the long term RES policy objective, the low scenarios relies more heavily on variable RES and flexibility sources

RES penetration

- In the low scenario, RES reach 94% of total 2050 generation, with **83% penetration of variable RES**.
- In the high scenario, RES reach 79% of total 2050 generation, with **69% penetration of variable RES**.

Storage

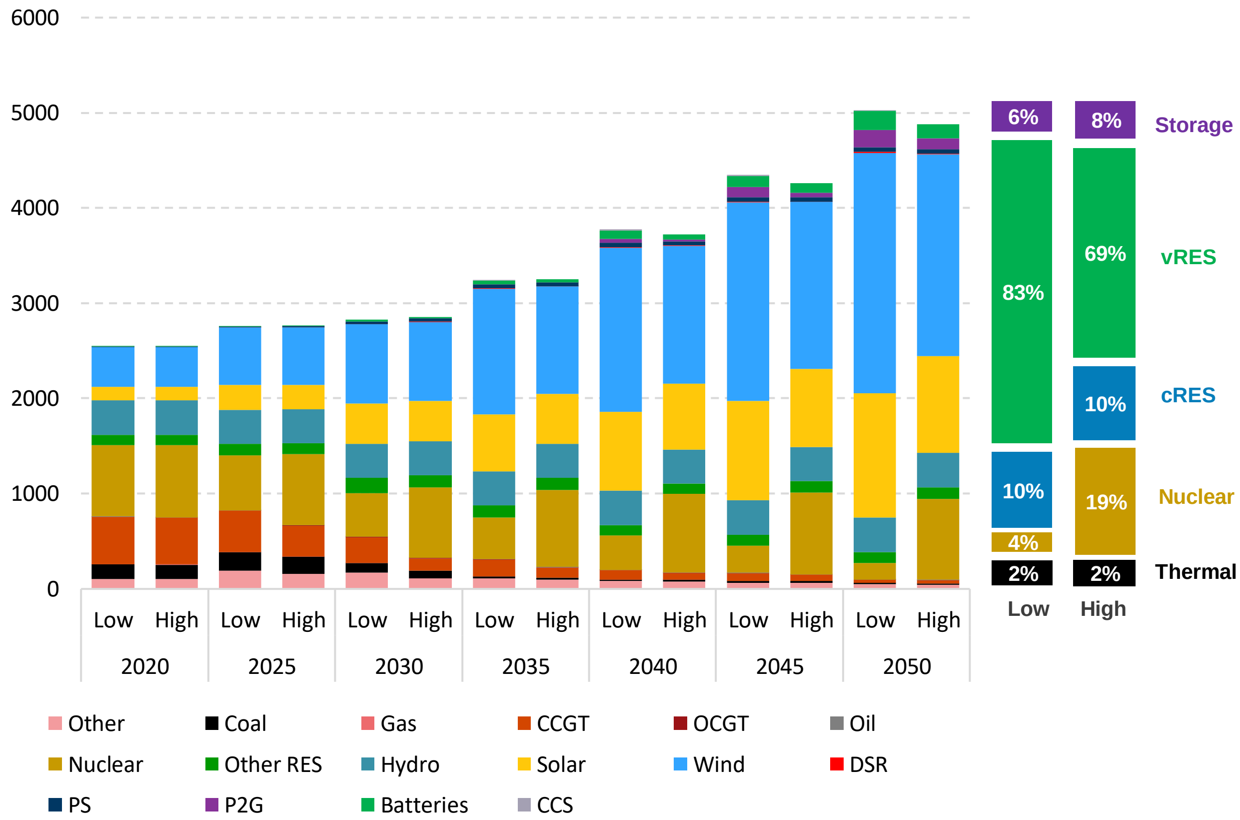
- In the low scenario, RES would produce 809 TWh of non directly consumed electricity, 386 of which being stored and redistributed through P2G or batteries.
- In the High scenario, RES would produce 559 TWh of non directly consumed electricity, 263 of which being stored and redistributed through P2G or batteries.

A reduction of 104 GW of nuclear capacity (resulting in 681 TWh reduced generation) would require bringing the variable RES share to around 83%.

A high nuclear scenario would entail a variable RES share of around 69%.

Note: Non-directly consumed RES production corresponds to storage net consumption (due to efficiency loss)

Low and High scenario generation outlook (TWh)



Note: Other includes small distributed thermal non-renewable generation; Wind includes onshore and offshore; PS stands for "Pumped Storage"; P2G stands for "Power to Gas"

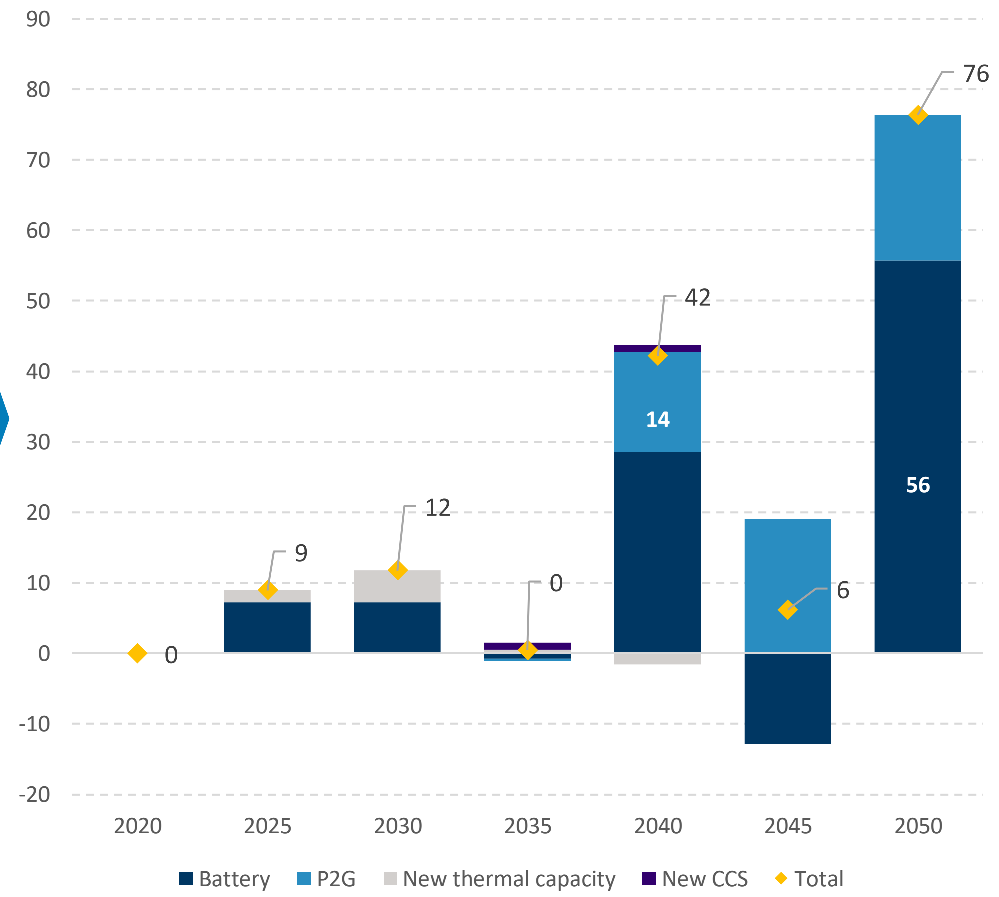
Source: CL Energy modelling

The Low nuclear scenarios increases investment requirements in thermal and storage technologies compared to the High scenario

A low nuclear generation share would materially increase the long term reliance of the power system on storage technologies, in particular long term / seasonal storage.

- **Over the modelling horizon, anticipated nuclear closure and limited new nuclear investments would require about 146 GW of additional new flexible resources until 2050:**
  - 5 GW of additional new thermal capacity would be built before 2030, to ensure security of supply– these investments would risk becoming stranded in the long run
  - 2 GW of additional new thermal CCS capacity would be built in the medium to long term
  - Given that batteries have a 10 years lifetime, it implies that c.85 GW of additional capacity would need to be commissioned between 2020 and 2050 to reach 56 GW capacity difference in 2050.
  - The additional requirement of long term storage in the low scenario would increase the reliance of the power system on yet to be proven technologies, especially considering that 14 additional GW would be required as soon as 2040.

Differences in new installed thermal and storage capacities between the Low and High scenarios (GW)



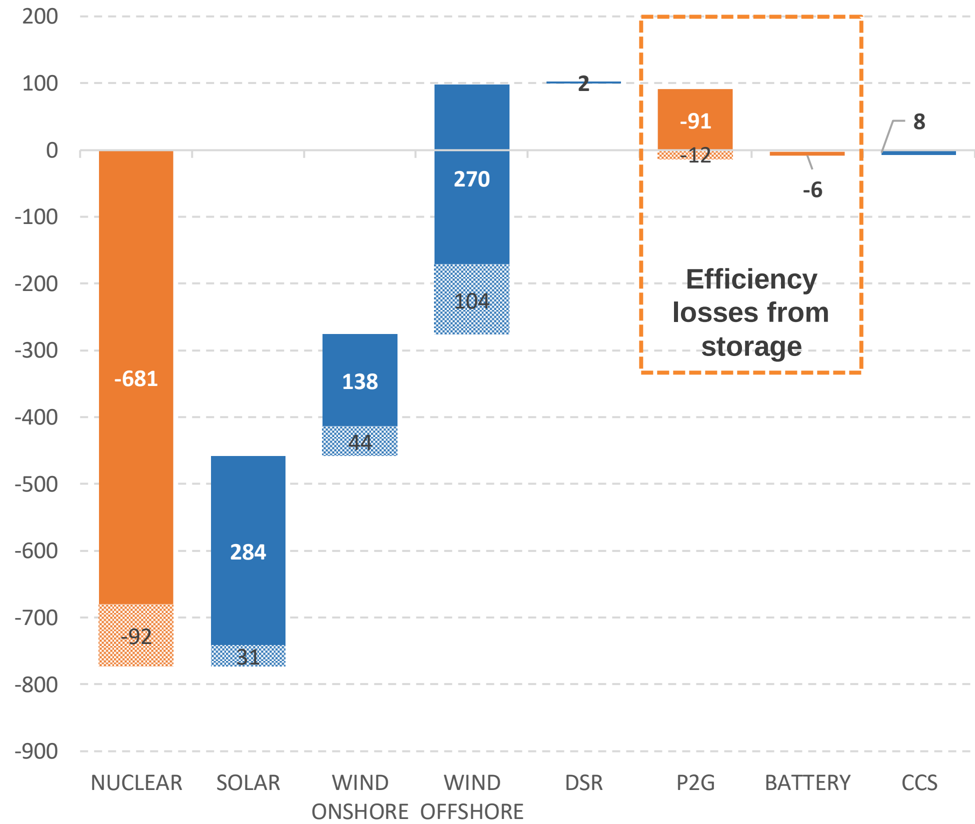
Source: CL Energy modelling

In the Low nuclear scenario reduced nuclear generation compared to the High scenario is made up by additional wind and solar generation

- **The 681 TWh reduced EU nuclear generation in 2050 (resulting from the reduction of nuclear capacities in the Low scenario by 104 GW) would be compensated by:**
  - 284 TWh Solar generation
  - 408 TWh Wind generation
  - 2 TWh of DSR
  - 8 TWh Generation from CCS

- **Three features are linked with the reduction of nuclear generation in the low scenario:**
  - A higher generation from the variable RES to compensate this reduction;
  - A higher generation and pump load from long term storage technology to smooth the periodic generation of variable RES...
  - …which results in an overall negative variation of the net generation (-91 TWh) as long term storage has an efficiency near 40%

Generation volume differences by technology between Low and High scenarios in 2050 (TWh)



Note: the figures in the text indicate the differences between low and high scenarios on the EU-27 scope (i.e. excluding the shaded areas on the chart which present the additional changes of capacity between the low and the high scenarios for the whole model's geographic scope)

Note: Net generation is represented for storage technologies

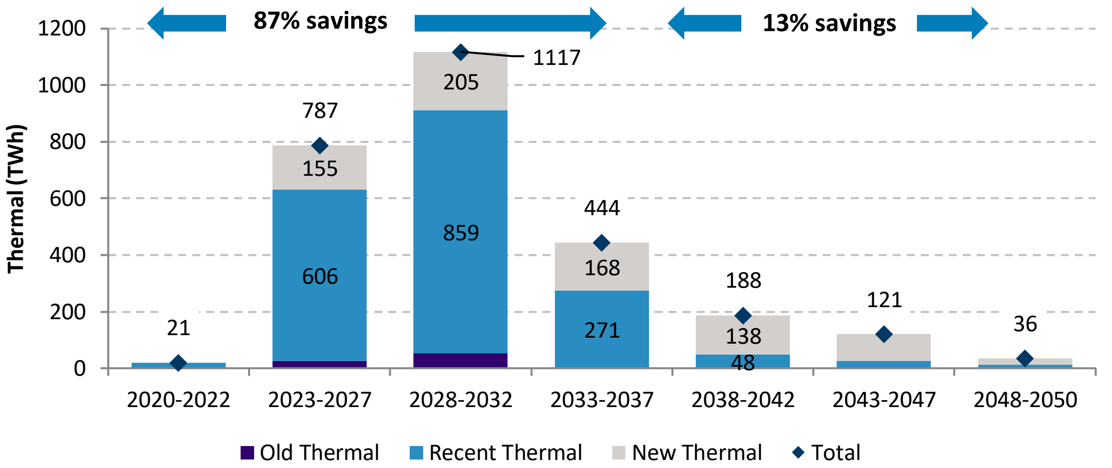
In the Low scenario, anticipated nuclear capacity closure increase thermal generation and curtailed energy from variable RES

Lower nuclear generation would heavily rely on thermal generation in the short to medium term before transitioning towards a less efficient generation mix featuring a much higher level of curtailed energy from variable RES.

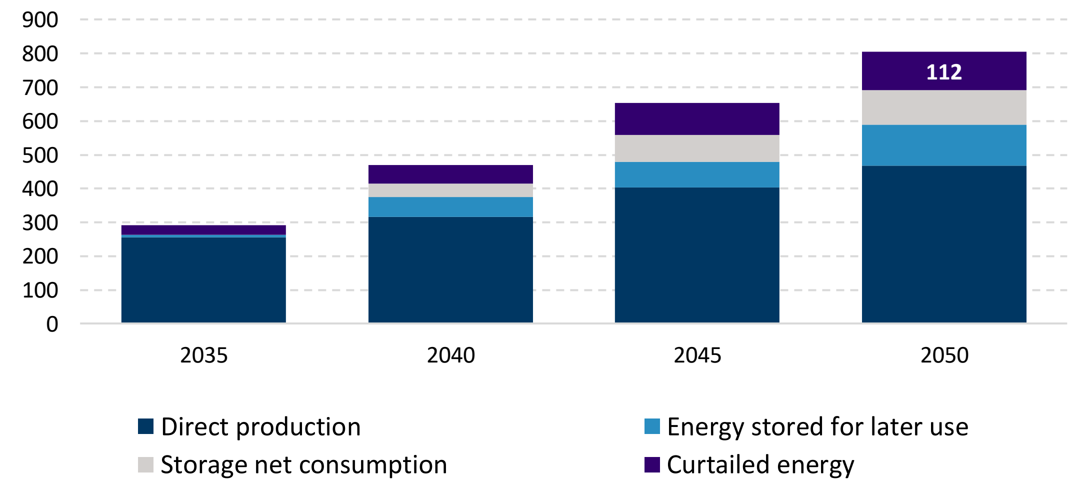
- **Anticipated closure of nuclear capacity (in the low scenario compared to the high scenario) would induce about 2370 TWh of additional thermal generation in the short term to medium term 2020-2037 period:**
  - This represents a **+22% increase** or the equivalent of 4 times an average year of projected thermal generation on this horizon.
  - Recent thermal plants take around 74% of this additional generation (1750 TWh) over 2020-2037.
- **In the longer term, anticipated nuclear closure and limited new nuclear investments in the low scenario would induce about 112 TWh of additional curtailed energy from RES in 2050, this represents:**
  - **16% of the vRES generation** difference between the low and high scenario; and
  - a **+87% increase** compared to the high scenario curtailment

Reduced curtailed energy illustrates the complementarity of nuclear with RES in the high scenario.

Thermal Generation differences between Low and High scenarios (TWh)



RES (wind, solar) generation differences between Low and High scenarios (TWh)



Source: CL Energy modelling

The nuclear average capacity factor remains above 70% over the entire 2020-2050 period

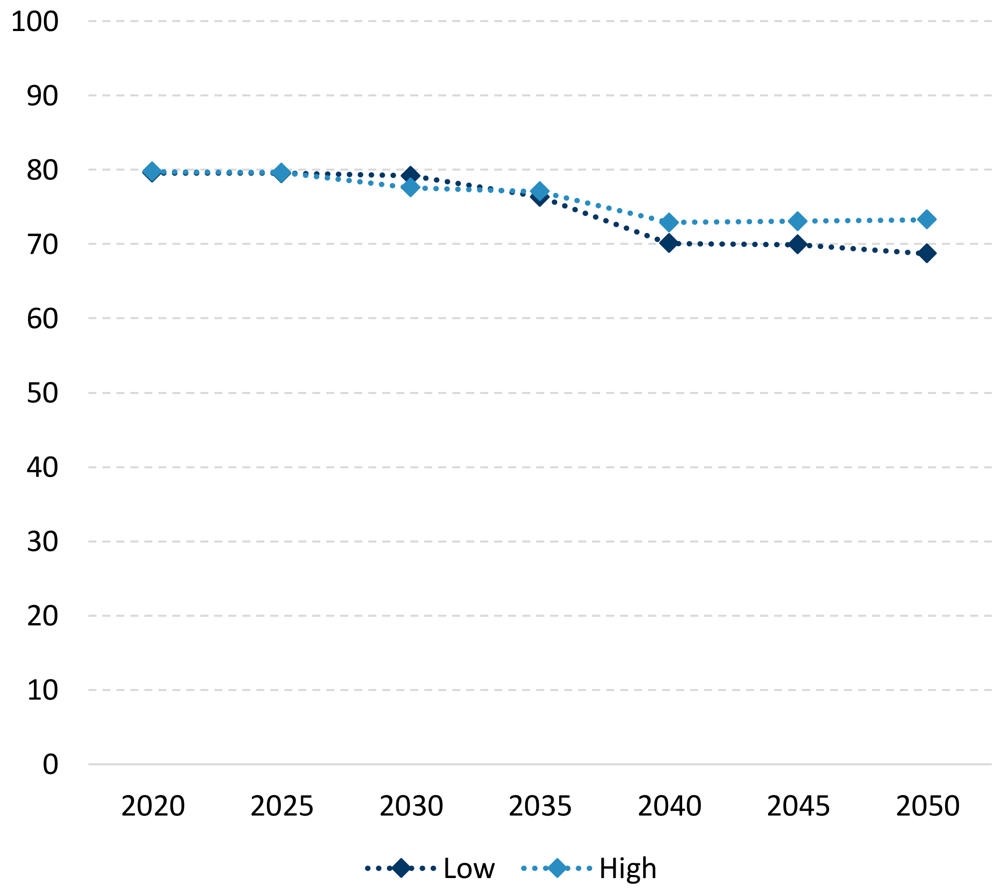
In both scenarios, the nuclear average capacity factor remains above 70% over the entire 2020 – 2050 period, except for the low scenario in 2050:

- In the Low nuclear scenario, faster growth of RES would further decrease nuclear average capacity factor.
- In the high scenario, lower RES penetration would enable to maintain a higher capacity factor in the long term.

A faster deployment of short term and seasonal storage would support a high utilisation of nuclear plants:

- With increasing renewable penetration, nuclear power would benefit from a timely deployment of storage to optimize its operation

Average nuclear capacity factor outlook (%)



Source: CL Energy modelling

Increased nuclear generation in the high scenario would reduce consumption of fossil fuels by up to 4150 TWh between 2020 and 2050

Increased nuclear generation in the High scenario compared to the Low scenario would avoid 3626 TWh of gas consumption between 2020 and 2050:

Equivalent to

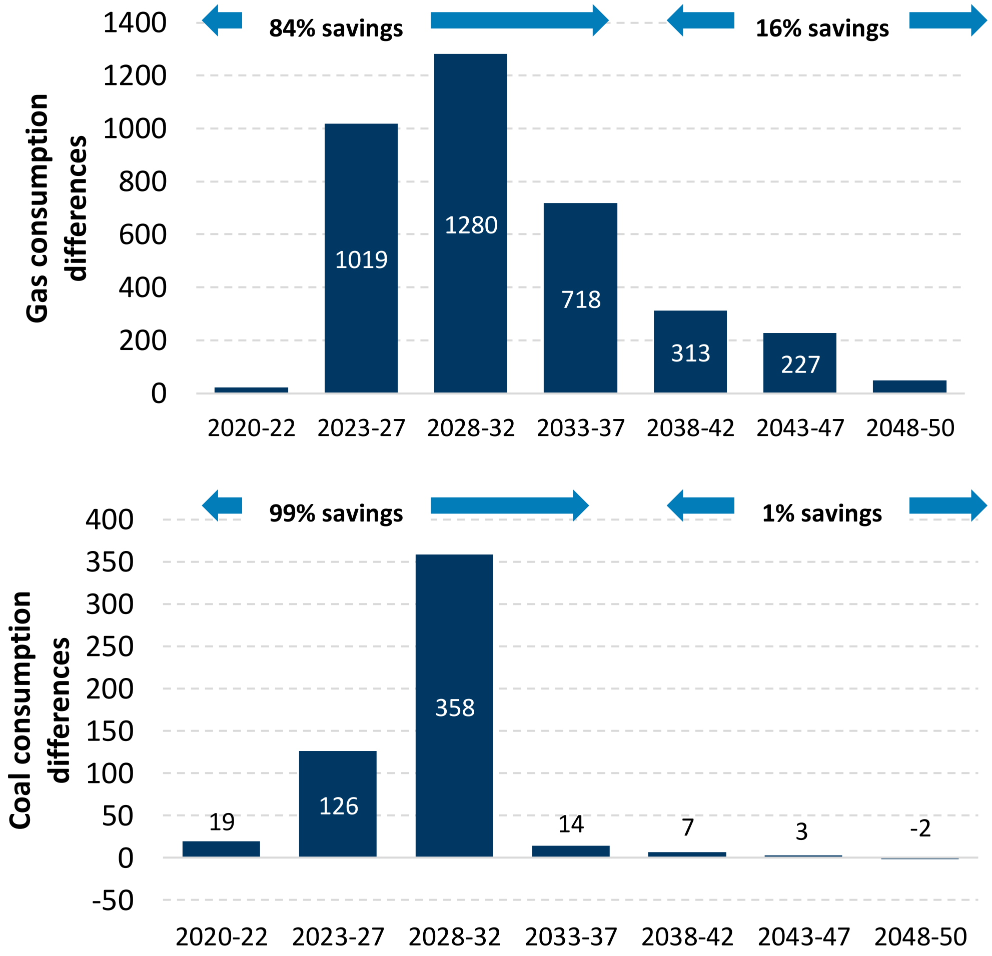
- 3.5 years of the low scenario 2020 gas consumption from the power sector, or
- **26% of the 2020-2050 overall gas consumption from the power sector in the low scenario**

Increased nuclear generation in the High scenario compared to the Low scenario would avoid 526 TWh of coal consumption between 2020 and 2050:

Equivalent to

- 1.5 years of the low scenario 2020 coal consumption from the power sector, or
- **12% of the 2020-2050 overall coal consumption from the power sector in the low scenario**

Fossil fuel consumption in the power sector differences between the High and the Low scenarios (TWh)



Source: CL Energy modelling

In the Low scenario, nuclear closure and limited nuclear investments would induce 1590 $MtCO_2$ of additional emissions in the short term

- While – by construction – both scenarios achieve the CO_2 emission reduction target in 2030 and the 2050 objective, **maintaining nuclear energy through extensions and new investments would significantly lower the CO_2 emission impact of the power sector, thereby further strengthening the role of electricity in the transition.**

Anticipated nuclear closure and limited new nuclear investments in the Low scenario would materially increase total emissions over 2020-2050:

- An early closure of nuclear plants would require new thermal plants in order to ensure security of supply, as well as additional thermal generation from existing plants which would generate **1590 Mt** of additional CO_2 emissions or **19% of total CO_2 emissions from the power sector** over 2020-2050 in the low scenario.

Furthermore, while most of the CO_2 savings would occur in the short to medium term (before 2035), facilitating the EU transition before further roll-out of variable renewable and storage, anticipated closure of nuclear in the low scenario would lead to increased CO_2 emission by 2025, thus jeopardizing 2030 increased ambition.

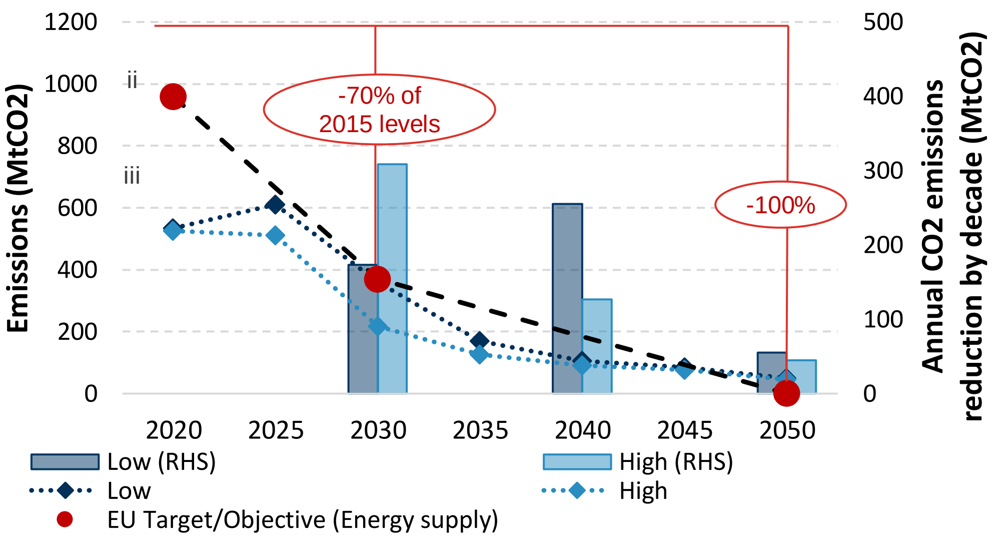
Note:

i) While both scenarios use a similar EU ETS price outlook, an increase of emission (resp, decrease) would put an upward pressure (resp. downward) on EU ETS price further impacting the cost to end-customers.

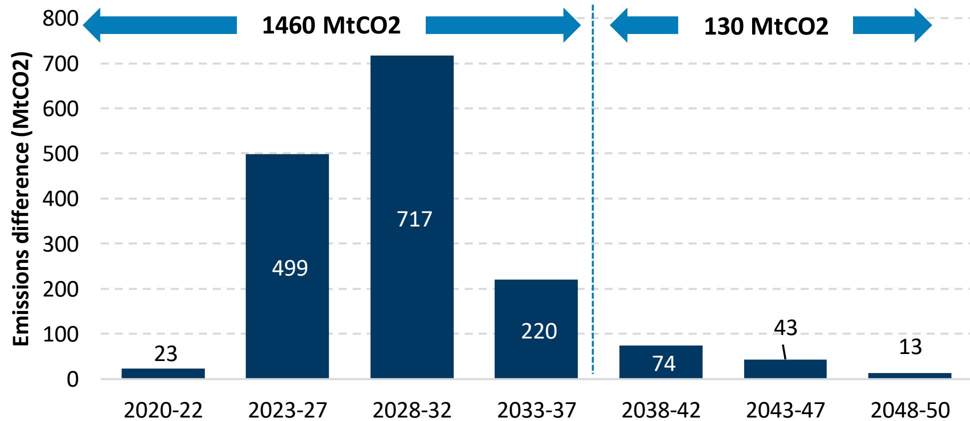
ii) The EU target 2020 for Energy supply emissions has been adapted to EU-27. To avoid corner solutions in the modelling, the 100% reduction of 2050 emitted CO2 is set slightly under this threshold.

iii) 2020 modelled CO2 emissions are much lower than the target as a result of the COVID-19 impact on power demand (-5% on average) and on thermal SRMCs, gas becoming more competitive than coal.

CO_2 emissions outlook for the power sector



Power sector CO_2 emissions difference Low minus High scenario (Mt CO_2)



Source: CL Energy modelling

In the low scenario, nuclear closure and limited nuclear investments would increase power prices throughout the modelled horizon

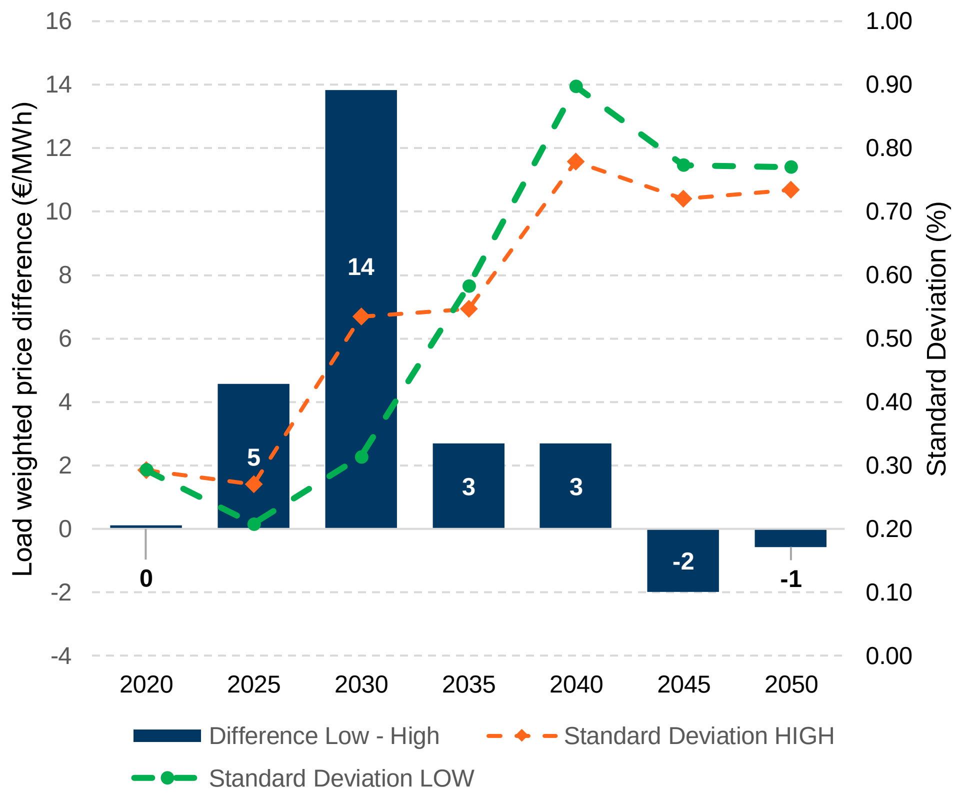
In the Low scenario, nuclear closure and limited nuclear investments would increase power prices throughout the modelled horizon.

- Across Europe, the power price impact of lower nuclear generation in the low scenario compared to the high scenario **averages at around 3.5€/MWh**, reaching 14€/MWh in 2030s when anticipated closures significantly increase fossil fuel consumption:
  - Anticipated nuclear closure would increase the frequency of gas-fired power plants and coal-fired power plants setting the price, leading to an increase of wholesale power prices.

The additional energy cost would affect the competitiveness of electricity versus other energies, which could affect the decarbonisation of the power sector by slowing down electrification of transport and heating & cooling.

Furthermore, the volatility of power prices increases significantly in both scenario, driven by the increasing variable RES penetration.

Power price outlook (real 2019) difference between Low and High scenarios



Note: Standard deviations are computed with the Time-Weighted price of the german bidding zone an normalized as a percentage of the average Time-weighted price observed each year

Source: CL Energy modelling

In the low scenario, customer cost would increase by about €392 billions over 2020-2050 compared to the high scenario

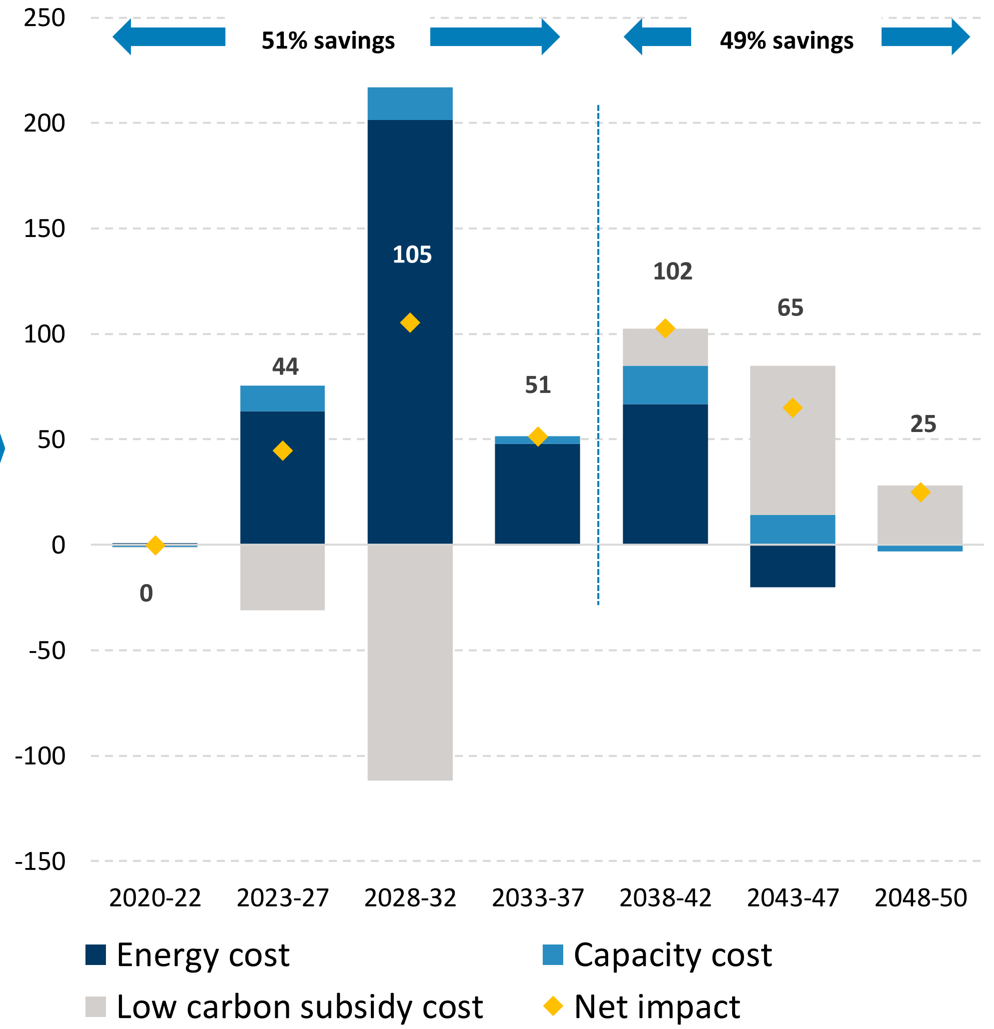
Anticipated nuclear closure in the low scenario compared to the high scenario would impact customer cost through:

- **Energy cost increase**:
  - **+€360 billion** additional cost as affordable nuclear baseload is replaced by more expensive gas and coal generation in the short to medium term;
- Partly enhanced by increased generation **capacity cost**:
  - **+€60 billion** mainly from the short term where anticipated nuclear closure leads to higher capacity prices
- And lower **low carbon subsidy cost**:
  - **-€27 billion** from reduced subsidies in low carbon generation in the short to medium term

Overall, the anticipated nuclear closure would increase total undiscounted customer cost by about €393 billion over 2020-2050, being 5% of total customer cost over 2020-2050 in the low scenario.

Note: Low carbon subsidy cost accounts for the subsidies (such as CfDs) that low carbon capacities would require to be economically viable while meeting the decarbonisation target.

Customer Cost difference (Billion €2019)



Source: CL Energy modelling

The low scenario would reduce residual value of investments by €942 billion in 2050 compared to the high scenario

The low scenario would increase investment cost by €98 billion over the high scenario:

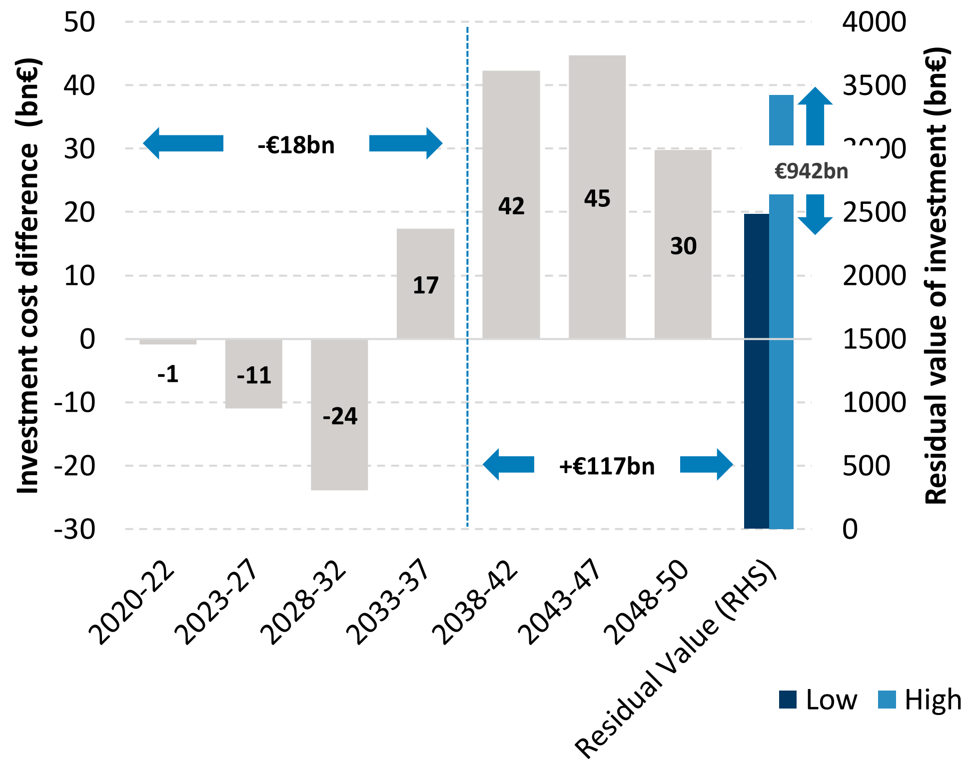
- Anticipated nuclear closure would save €18 billion in the short to medium term before increasing investment cost by €117 billion in the long term.
- It represents a 4% increase of the investment cost compared to the high scenario.

The low scenario would decrease the residual value of investment by €942 billion in 2050 compared to the high scenario (27.5% decrease):

- The high scenario 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 taken into account 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

Annualized investment cost difference over 2020-2050 and residual value (Billions €2019)



Source: CL Energy, generic nuclear capex input from FORATOM

The sensitivity analysis on nuclear capex reduction shows that investment and customer costs findings remain positive

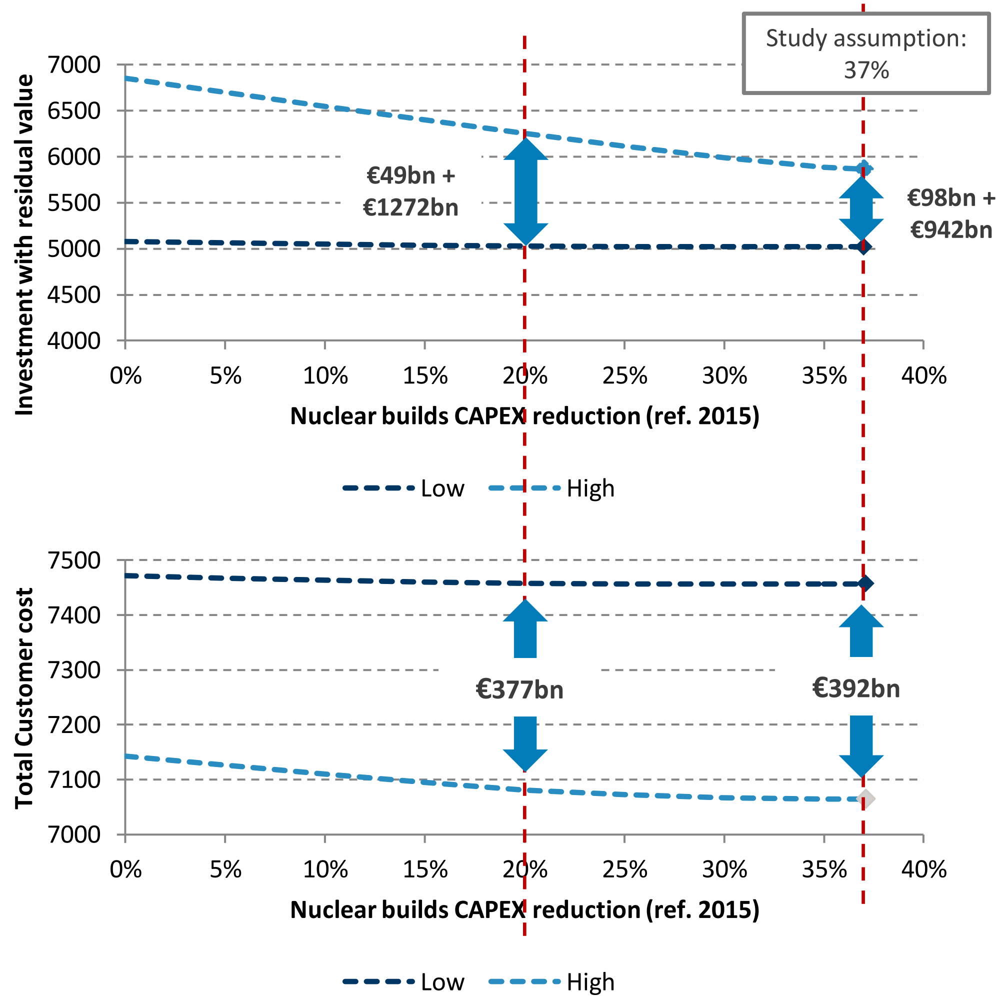
In the High scenario, costs are more sensitive to the nuclear CAPEX reduction assumption, but results remain consistent when the nuclear CAPEX reduction assumption is less ambitious:

- At a maximum 20% CAPEX reduction from the 2015 value over the horizon (instead of the initial capex trajectory which reaches 37% reduction in 2050) , investment costs savings during 2020-2050 would decrease from €98bn to €49bn, while residual value benefits would increase from €942bn to €1272bn.
- At a maximum 20% CAPEX reduction from the 2015 value over the horizon (instead of the initial capex trajectory which reaches 37% reduction in 2050), total customer costs benefits would remain at a similar level, reducing from €392bn to €377bn.

Benefitting fully from the potential cost reduction would materialise through:

- Standardized reactors designed from lessons learned on FOAK
- Several cost reduction opportunities materialisation in digital, high performance concrete, modularity, …
- Policy makers to design long term nuclear strategic plans through long term support schemes (CfD, RAB model) and recognition of the nuclear contribution to decarbonisation

Sensitivity of investment and costs to nuclear capex maximum reduction over the horizon (Billions €2019)



A. Detailed impact assessment results

Estimates derived from the literature of indirect costs and externalities

Methodology for estimates derived from the literature of indirect cost and other criteria

To complement the power market modelling outputs related to the dispatch and the long-term investment decisions, we rely on high level estimates derived from a literature review to estimate the indirect costs and other criteria used for the impact assessment in the two scenarios modelled.

Note that a thorough modelling of the effect of different decarbonisation scenarios on these indicators listed in this section is beyond the scope of this study. The high-level estimates derived from the literature provided should be therefore considered as orders of magnitude rather than precise quantifications.

In this section , we rely on assumptions derived from a literature review to derive high level estimates of the following criteria:

- Labour impact;
- Transmission and Distribution (T&D) cost;
- Balancing cost;
- Land use;
- SO2 emission;
- NOx emission; and
- Particular Matter emission;

Estimates derived from the literature of labour intensity for the nuclear technology

Literature review

- The different forms of electricity generation require various workforce quantity of different skill level.
- This can be counted as an indirect effect of technologies on employment and growth.
- The study from OECD Nuclear Energy Agency and the IAEA (International Atomic Energy Agency) uses an Input-Output (I-O) modelling to study macro-economic impacts from energy technologies.
- The I-O modelling captures multiple levels of actions on employment by technology:
  - Direct employment: employee working full-time on power production sites
  - Indirect employment: employee working full-time in the supply chain
  - Induced employment: employees in the related economy

Estimate of direct job by the nuclear technology in the literature

- The 2018 study from OECD Nuclear Energy Agency in partnership with the IAEA about measuring employment generated by the nuclear sector provide quantitative data in the US, France and Korea for Gen III NPP
- This assessment is based on the data from labour workforce needed during the different phases from a nuclear power plant's life (building, operation, decommissioning, nuclear fuel and waste management)
- Nuclear technology is one of the most direct job intensive technology with an estimate around 0.5 direct jobs/MW varying with the country studied decomposed for a 1 GW generic NPP as:
  - 1200 workers for a 10 years building phase or 12k labour-years
  - 600 workers for a 50 years O&M phase or 30k labour-years
  - 500 workers for a 10 years decommissioning phase or 5k labour-years
  - 80 workers for a 40 years waste management phase of c. 3k labour years
- We keep this conservative value as it becomes challenging to forecast long term parameters improvement, such as learnings and feedbacks from development and experience

Source: NEA, IAEA 2018

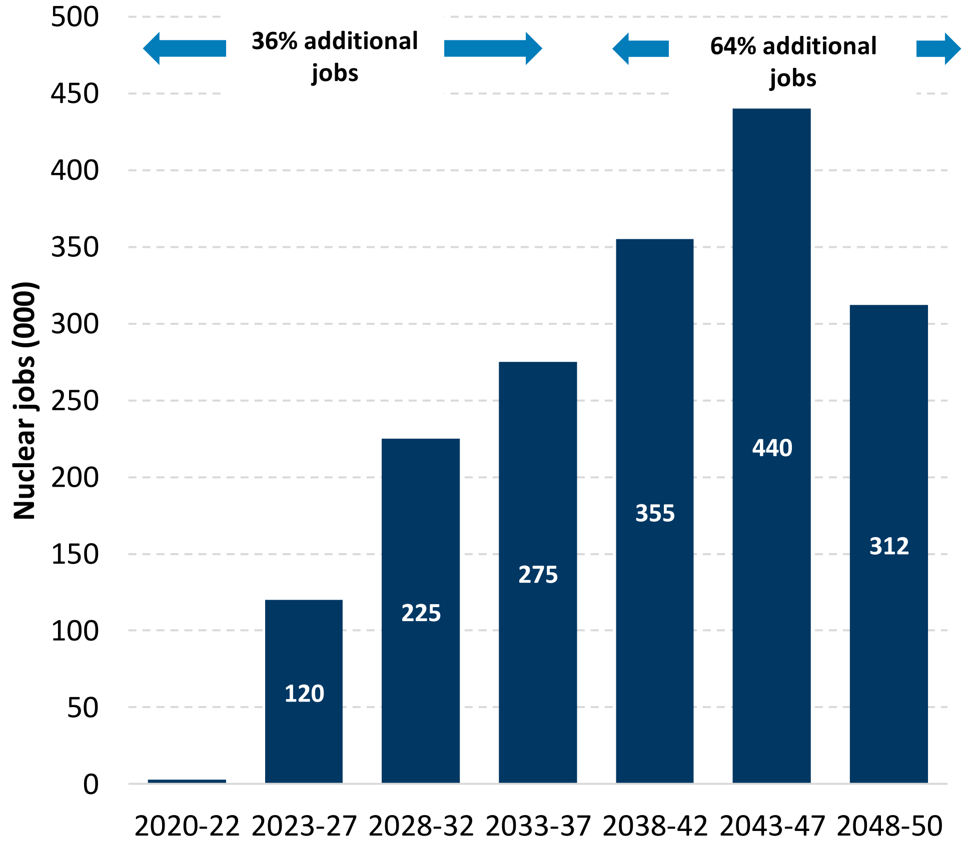
A higher share of nuclear power would create more direct job-years in the nuclear generation sector over 2020-2050 thanks to its high labour intensity

Whilst a thorough modelling of the effect on employment of different decarbonisation scenarios is beyond the scope of this study, we provide below rough estimates in the two scenarios based on the assumptions derived from our literature review.

A higher nuclear share would positively impact the number of direct jobs in the nuclear generation sector, providing additional direct jobs:

- An extension of nuclear plants followed by new investments across Europe would create an estimate derived from the literature of 1730 thousands additional direct jobs in the nuclear generation sector over 2020-2050, or +86% compared to the Low scenario.

Direct job impact difference derived from the literature between high and low scenarios in the nuclear generation sector



Source: CL Energy modelling

Estimates derived from the literature of transmission and distribution costs

Literature review

- While grid costs are similar for all type of generating plants, differences exist as:
  - The connection could be directly to the distribution grid for smaller sites (typically 0.1 to 100MW compared to >500MW for conventional plants);
  - The average utilisation would depend on the capacity factor of the generator; and
  - Sites with best RES resources might be located far from demand centres.
- Major analytical efforts have been conducted to estimate grid costs in various European countries:
  - A study of grid integration costs of PV commissioned by the European Commission in 2014 and carried out by the Imperial College London ;
  - A study of the integration of the RES commissioned by the European Commission in 2014 carried out by KEMA/Imperial College London/NERA/DNV GL;
  - A study of the full costs of electricity provision carried out by the Nuclear Energy Agency in 2018.

Average T&D costs from literature review

- The literature shows large variations reflecting the specific features of each individual site and different power systems.
- However based on the literature review, we can infer the following estimates, which represent an “average” of different estimates found in the literature.

€/MWh	Transmission cost	Distribution cost	Offshore grid	Total
Solar PV	1.5	6		7.5
Wind onshore	5	6		11
Wind offshore	5	n/a	30	35

Source: Agora (2015) The Integration Costs of Wind and Solar Power

In the low scenario, the faster growth of RES would induce additional costs through the channels of transmission and distribution grid costs

Whilst a thorough modelling of the T&D grid costs in the different decarbonisation scenarios is beyond the scope of this study, we provide below rough estimates based on the assumptions derived from our literature review.

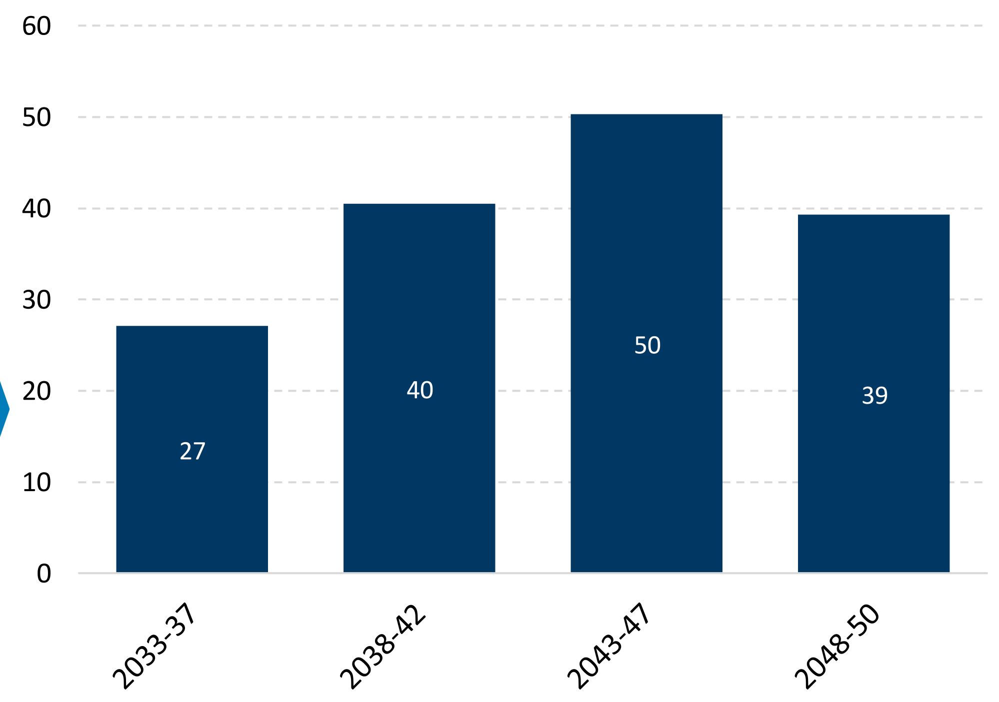
The low scenario with a higher share of RES would increase T&D grid costs compared to the high scenario:

- An early closure of nuclear plants, and no new nuclear new investments would require new solar and wind capacities in order to meet environmental objectives, which would generate about an estimate derived from the literature of **€158 billion of additional T&D grid costs or 17% of the total T&D grid cost cumulatively over the 2020-2050 horizon**, of which €26 billion comes from offshore grid cost.
- This additional cost would materialize in the long term when variable RES penetration increase significantly to achieve the decarbonisation objective.

A high nuclear share would therefore lead to significant benefits in terms of future additional Transmission and Distribution grid costs as derived from the literature.

Adding to customer cost benefits, it would bring total benefits to €550 billion over 2020-2050.

T&D grid costs differences derived from the literature between low and high scenarios (Billion €2019)



Note (1): T&D cost shown on the chart above are the additional T&D cost between 2020 and 2050 resulting from the difference of high and low scenarios grid costs. As the expansion of RES capacity diverges the low scenario after 2030, the almost whole additional grid costs is after this date hence, the reduce time scope in this graph

Note (2): Offshore connection costs for Offshore Wind are accounted in the total investment cost (slide 33) as per EC convention.

Source: CL Energy modelling

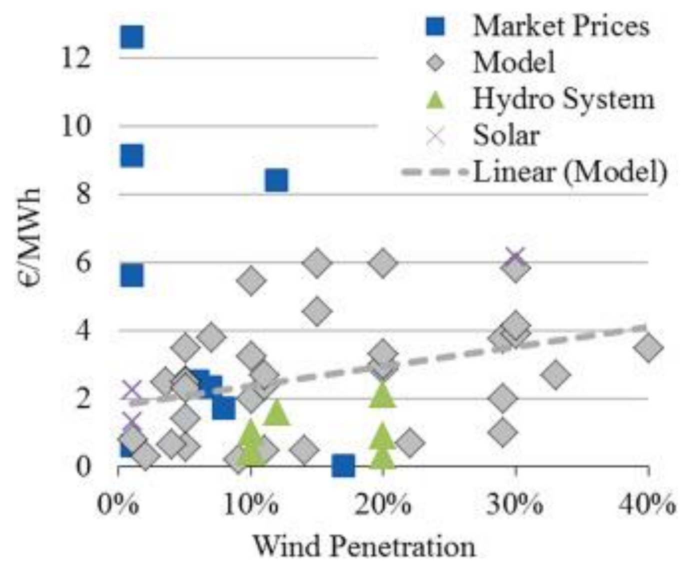
Estimates derived from the literature of balancing cost

Literature review

- Balancing costs are the costs incurred in balancing the deviations between the actual generation and the forecasted generation.
- Variable renewable being weather dependent are subject to forecast errors, which in turn increase the requirement of holding and using balancing reserves.
  - The impact on the amount of reserves required increases with the penetration level of renewables
- Conversely, the smaller size of RES generation compared to other conventional plants enables to reduce the impact of technical failures of a generator on the power system.
  - Fewer reserves are required to offset the failure of renewable generators than in the case of large power plants
- There are different types of studies that provide RES balancing cost estimates:
  - Integration studies commissioned by SO;
  - Academic publication based on unit commitment models;
  - Empirical studies based on market price.

Balancing costs from literature review

- Hirth (2015) has summarized results in "Integration costs revisited – An economic framework for wind and solar variability"
  - Balancing cost estimates for wind and power from market prices (squares) and model prices (diamonds) for wind and solar power (crosses). Three market-based studies report very high balancing costs. All other estimates are below 6 €/MWh. Studies of hydro-dominated systems show low balancing costs (triangles).
- We therefore assume costs of 2€/MWh and 1€/MWh for wind (onshore & offshore) and solar respectively



Source: Hirth (2015)

In the low scenario, faster growth of RES would impact upward total balancing costs

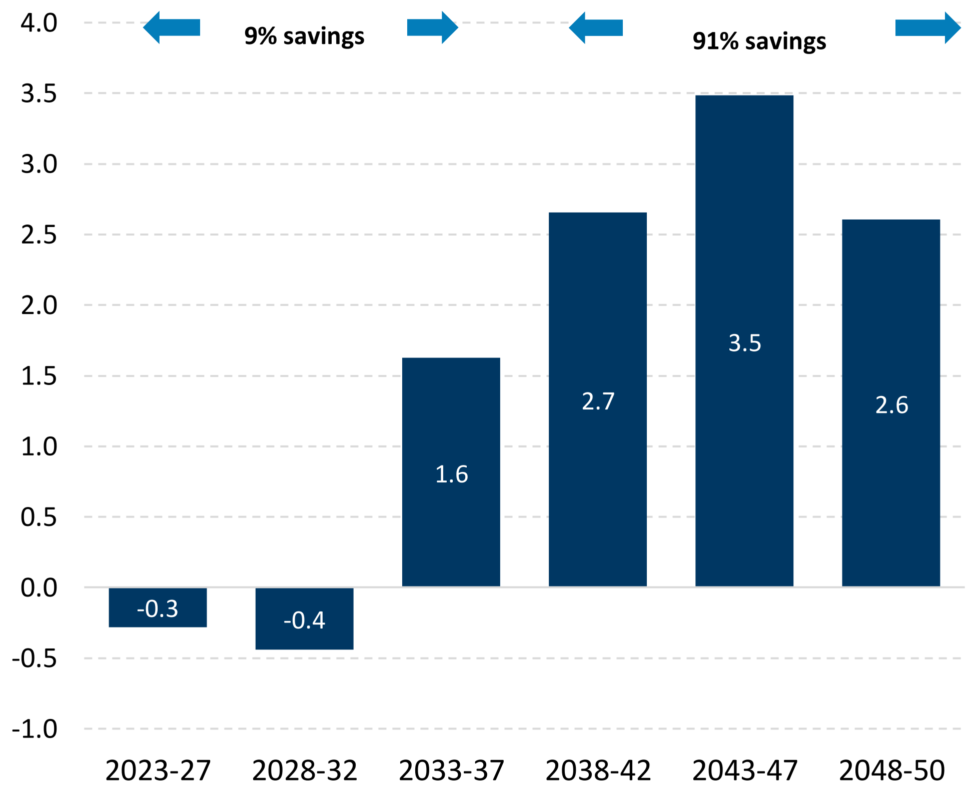
Whilst a thorough modelling of the effect on balancing costs of different scenarios is beyond the scope of this study, we provide a rough estimate based on the assumptions derived from our literature review.

In the low scenario, faster growth of RES and anticipated nuclear closure would increase balancing costs estimates derived from the literature by €10 billion compared to the high scenario over the 2020-2050 period:

- An early closure of nuclear plants would require new solar and wind capacities in order to meet environmental objectives, which would generate an estimate derived from the literature of **€10 billion of additional balancing costs or 9% of total balancing costs over the modelled horizon**.

Adding to customer cost benefits and T&D costs benefits, it would bring total benefits to about €560 billion over 2020-2050.

Balancing costs differences derived from the literature between low and high scenarios (Billion €2019)



Source: CL Energy modelling

Estimates derived from the literature of land use by generation technology

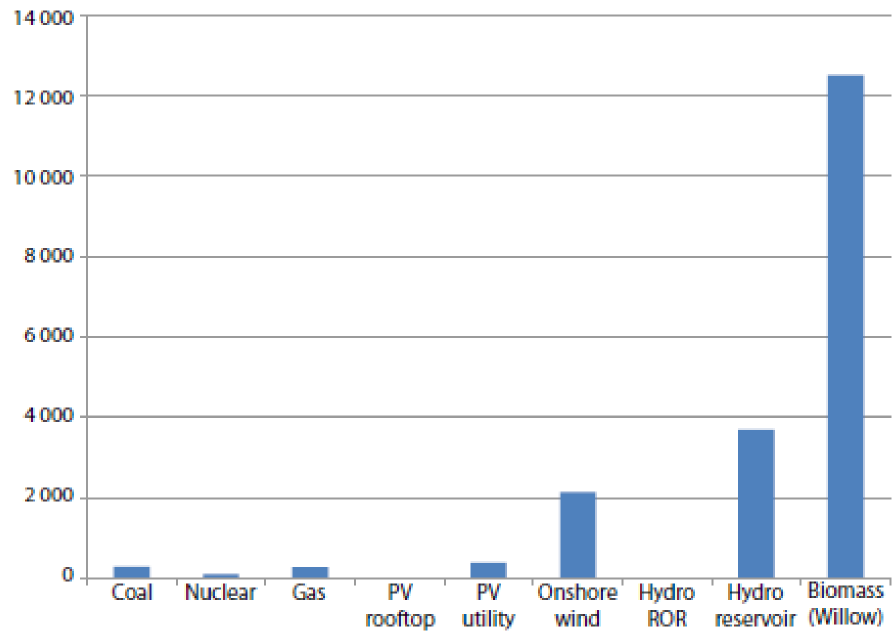
Literature review

- Different forms of electricity generation can have a large impact on the land they use.
- While assessing the costs of land-use change is difficult, the geographic footprint (i.e., land-use requirements of different technologies measured in square meters) can be seen as “a useful but very imperfect proxy for the severity of the public policy issues raised by them”. (NEA, 2018)
- An often-cited study in the land use of the power sector field of research is the study from Fthenakis and Kim (2009).
  - The study conducted life cycle land-use estimates for renewable as well as for coal, nuclear and natural gas.
  - Land use patterns of renewable and non-renewable sources are different especially in a dynamic perspective.
  - While the land occupation rate for non-renewable sources, in particular fossil fuels, is dependent on the fuel extraction rate, for renewable sources, once the capacity is installed, land use no longer increases.

Land use requirement derived from the literature for different technologies

- While all renewable sources share the quality of having a constant land occupation over the time of generation, the variation in land requirements is greater both quantitatively and qualitatively than among non-renewable sources (Fthenakis and Kim, 2009).

(Life-cycle assessment including mining and transport, m^2/GWh)



Source: Based on Fthenakis and Kim, 2009.

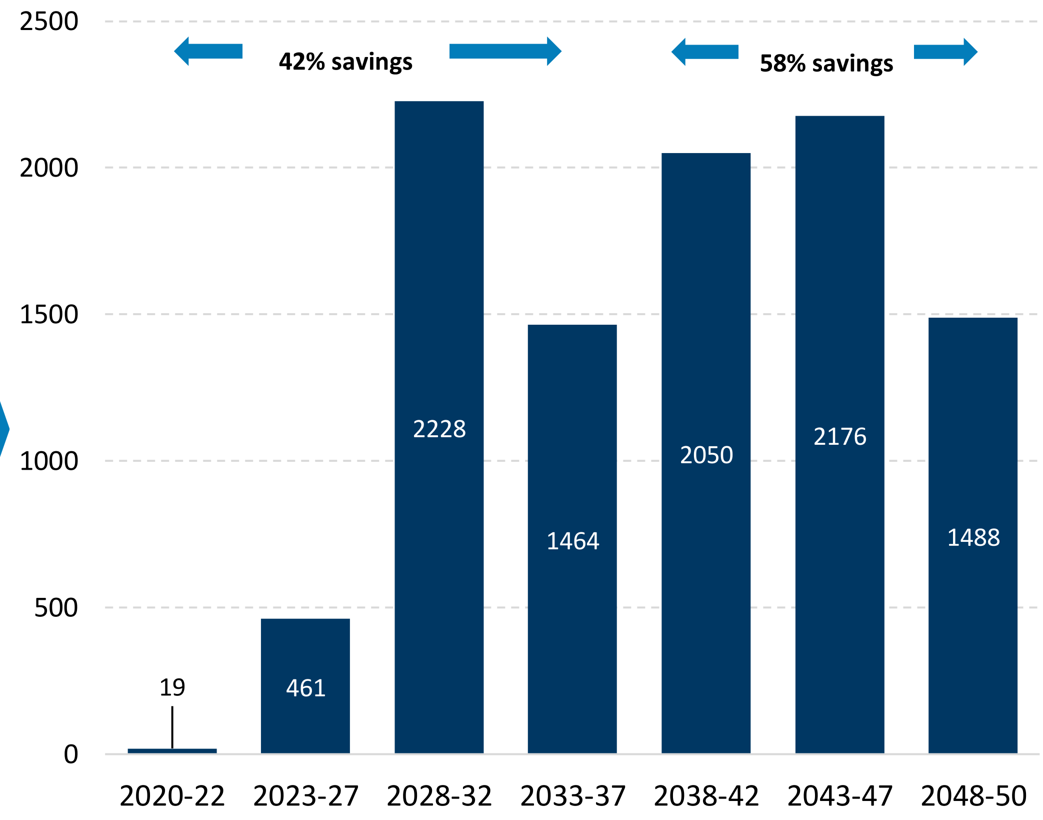
In the high scenario, nuclear generation could reduce an additional land use because of lower land requirements compared to other technologies

Whilst a thorough modelling of the effect on land use of different decarbonisation scenarios is beyond the scope of this study, we provide below rough estimates in the three scenarios based on the assumptions derived from our literature review.

In the low scenario, nuclear closure and faster growth of RES would increase land use as compared to the high scenario:

- An early closure of nuclear plants would require new solar and wind capacities in order to meet environmental objectives, which would generate an estimate derived from the literature of **9890 km2 of additional land requirement or 7% of total land use over 2020-2050**.
- This would be a bit less than four times Luxemburg area.

Land use differences derived from the literature between high and low scenario (km2)



Source: CL Energy modelling

Estimates derived from the literature of NOx, SO2 and Particular Matter (PM) emissions

Literature review

- The World Health Organization ("WHO") refers to air pollution as the world's largest environmental health risk. WHO studies from 2014 and 2016 find that in 2012 around 3 million people died due to ambient air pollution, to which electricity generation is a major contributor (WHO, 2014a, 2014b and 2016).
  - "Few risks have a greater impact on global health today than air pollution" (WHO, 2016)
  - According to the IEA, fossil fuel-based power generation is responsible for one-third of SO2 emissions, 14% of NOx emissions and 5% of PM emissions.
  - Inside the power sector, coal combustion generates between 70% and 90% of the sectors contribution to the three key pollutants (IEA, 2016a: pp. 26-44).
- In Europe, acknowledging the importance of these environmental externalities, the ExternE ("External Costs of Energy") approach has been set up in the early 90s to develop an approach of calculating environmental external costs through a series of projects.

NOx, SO2 and PM emissions from literature review

- Fossil-fuel sources (coal, natural gas, oil and biomass) emit local air pollutants during electricity generation, while non-carbon-based sources (nuclear, wind, solar, hydro, geothermal and tidal) emit either few or no air pollutants during generation, with some indirect emissions resulting from the manufacture of steel and concrete for the power plant construction. (Full cost of electricity NEA, 2018)

	mg/kWh	SO_2	NO_x	PM	Hg
Coal	Hard coal	530-7 680	540-4 230	17-9 780	0.01-0.037
	Lignite	425-27 250	790-2 130	113-947	Insufficient data
Natural gas	Combined-cycle	1-324	100-1 400	18-133	Insufficient data
	Steam turbine	0-5 830	340-1 020	Insufficient data	Insufficient data
Nuclear		11-157	9-240	0-7	Insufficient data
Bioenergy		40-490	290-820	29-79	Insufficient data
Solar	Photovoltaic	73-540	16-340	6-610	~0
	CSP	35-48	54-160	7-26	Insufficient data
Geothermal		0-160	0-50	1.3-50	~0
Hydropower	Reservoir	9-60	3-13	0.1-25	Insufficient data
	River	1-6	4-6		Insufficient data
Ocean/tidal		64-200	49	15-36	Insufficient data
Wind		3-88	10-75	1-14	~0

Source: Based on Masanet et al., 2013.

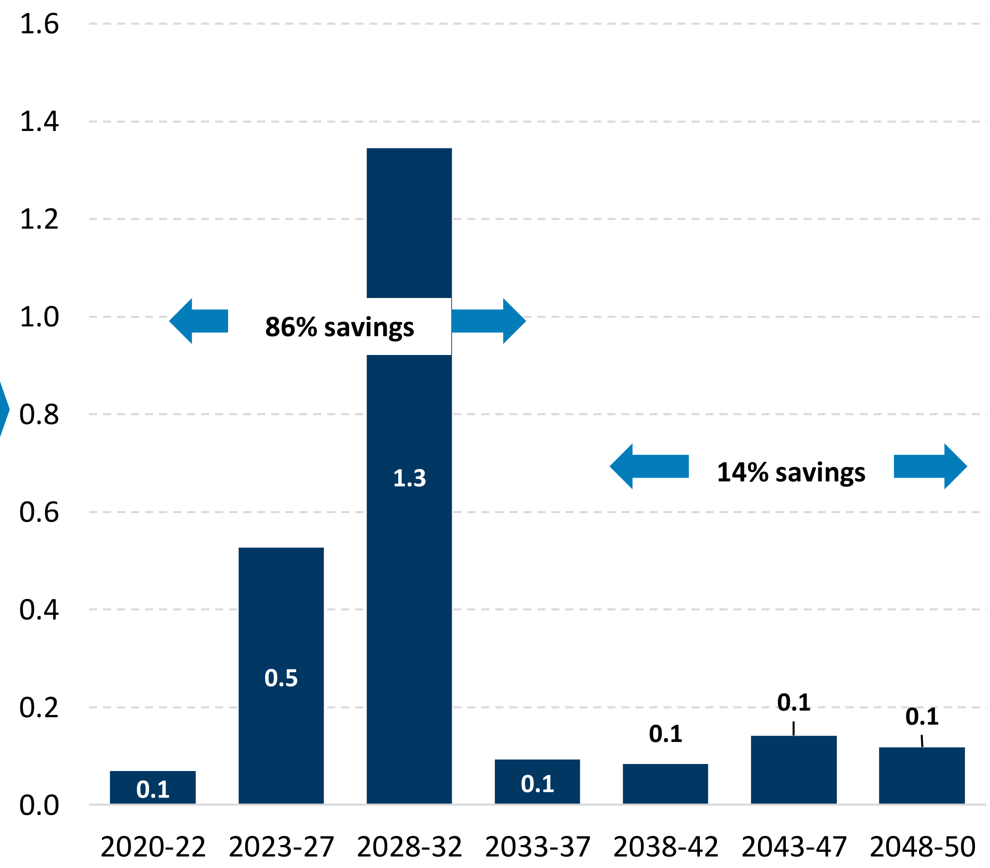
In the low scenario, SO2 emissions would increase because of thermal and RES generation differences

Whilst a thorough modelling of the impact on SO2 emissions of different decarbonisation scenarios is beyond the scope of this study, we provide below rough estimates in the two scenarios based on the assumptions derived from our literature review.

In the low scenario, anticipated closure would increase SO2 emissions compared to the high scenario:

- An early closure of nuclear plants would require new thermal capacities in order to ensure security of supply, as well as additional thermal generation from existing plants which would generate an estimate derived from the literature of **2.4Mt of additional SO2 emissions or 7.7% of total SO2 emissions over 2020-2050 in the low scenario.**

Differences in SO2 emission estimates derived from the literature between low and high scenarios (Mt)



Source: CL Energy modelling

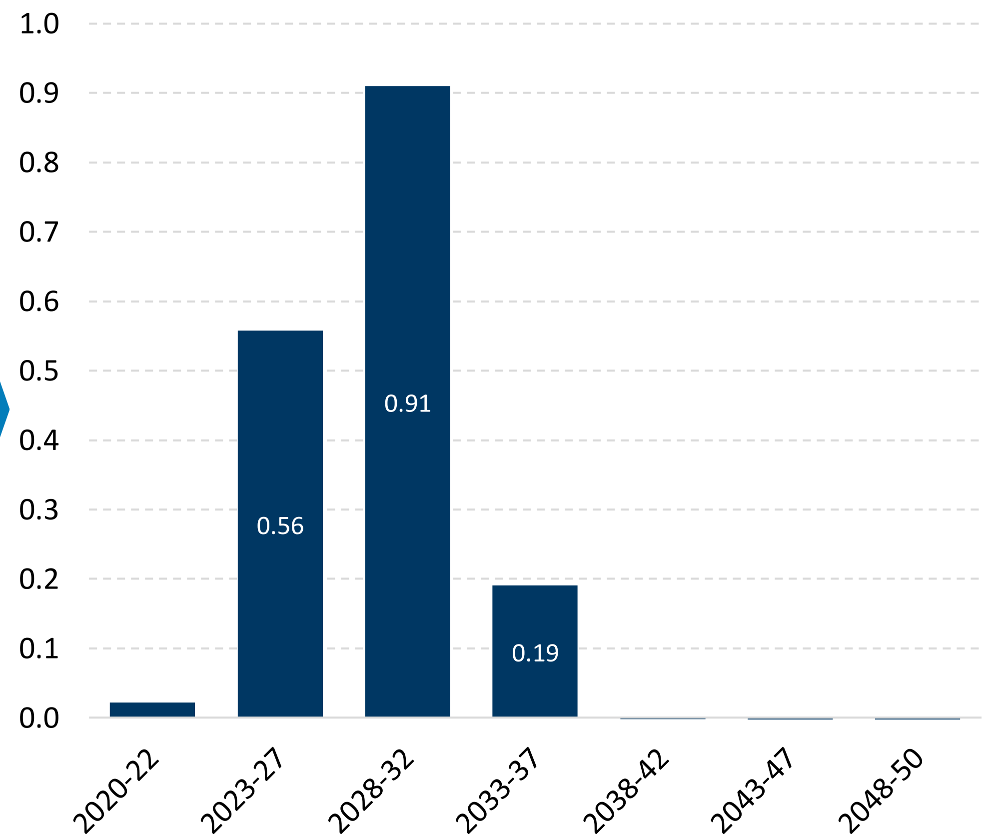
In the low scenario, NOx emissions would increase because of thermal and RES generation differences

Whilst a thorough modelling of the impact on Nox emissions of different decarbonisation scenarios is beyond the scope of this study, we provide below rough estimates in the three scenarios based on the assumptions derived from our literature review.

In the low scenario, anticipated closure would increase NOx emissions compared to the high scenario:

- An early closure of nuclear plants would require new thermal capacities in order to ensure security of supply, as well as additional thermal generation from existing plants which would generate an estimate derived from the literature of **1.6Mt of additional NOx emissions or 7% of total NOx emissions over 2020-2050 in the low scenario.**

Differences in NOx emission estimates derived from the literature between low and high scenarios (Mt)



Source: CL Energy modelling

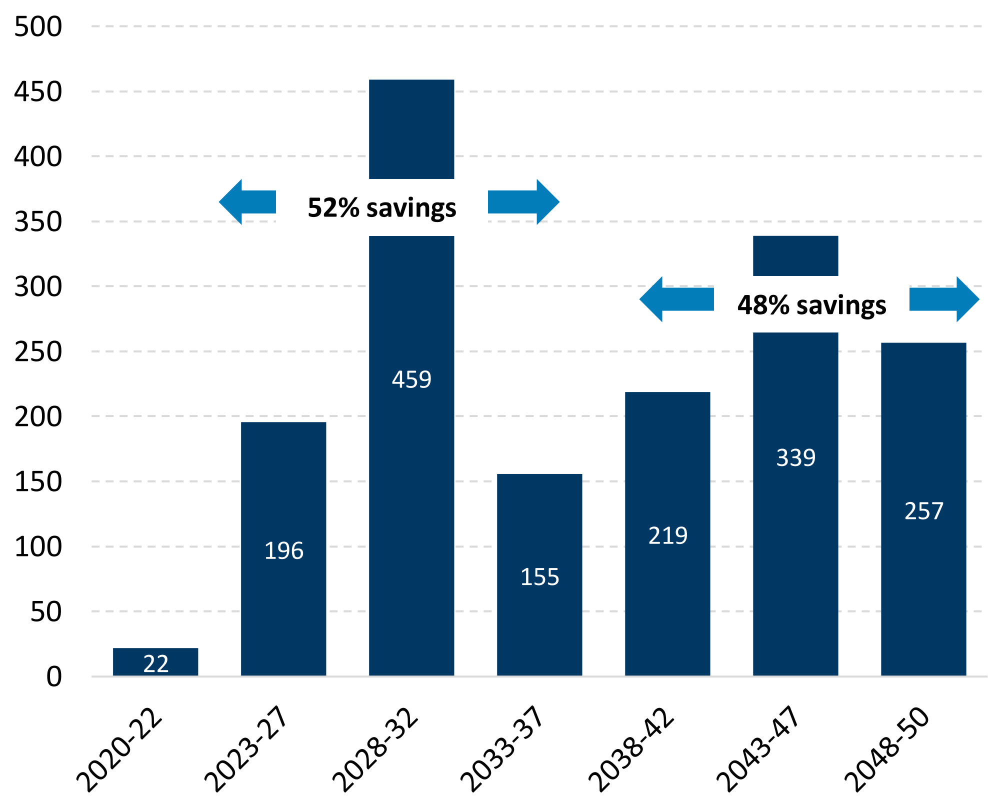
In the low scenario, particulate matter emissions would increase mainly because of solar capacity development

Whilst a thorough modelling of the impact on particulates emissions of different decarbonisation scenarios is beyond the scope of this study, we provide below rough estimates in the three scenarios based on the assumptions derived from our literature review.

In the low scenario, anticipated plant closure would increase PM emissions compared to the high scenario:

- An early closure of nuclear plants would require new thermal capacities in order to ensure security of supply, as well as additional thermal generation from existing plants which would generate an estimate derived from the literature of **1650kt of additional PM emissions or 12% of total PM emissions over 2020-2050 in the low scenario.**

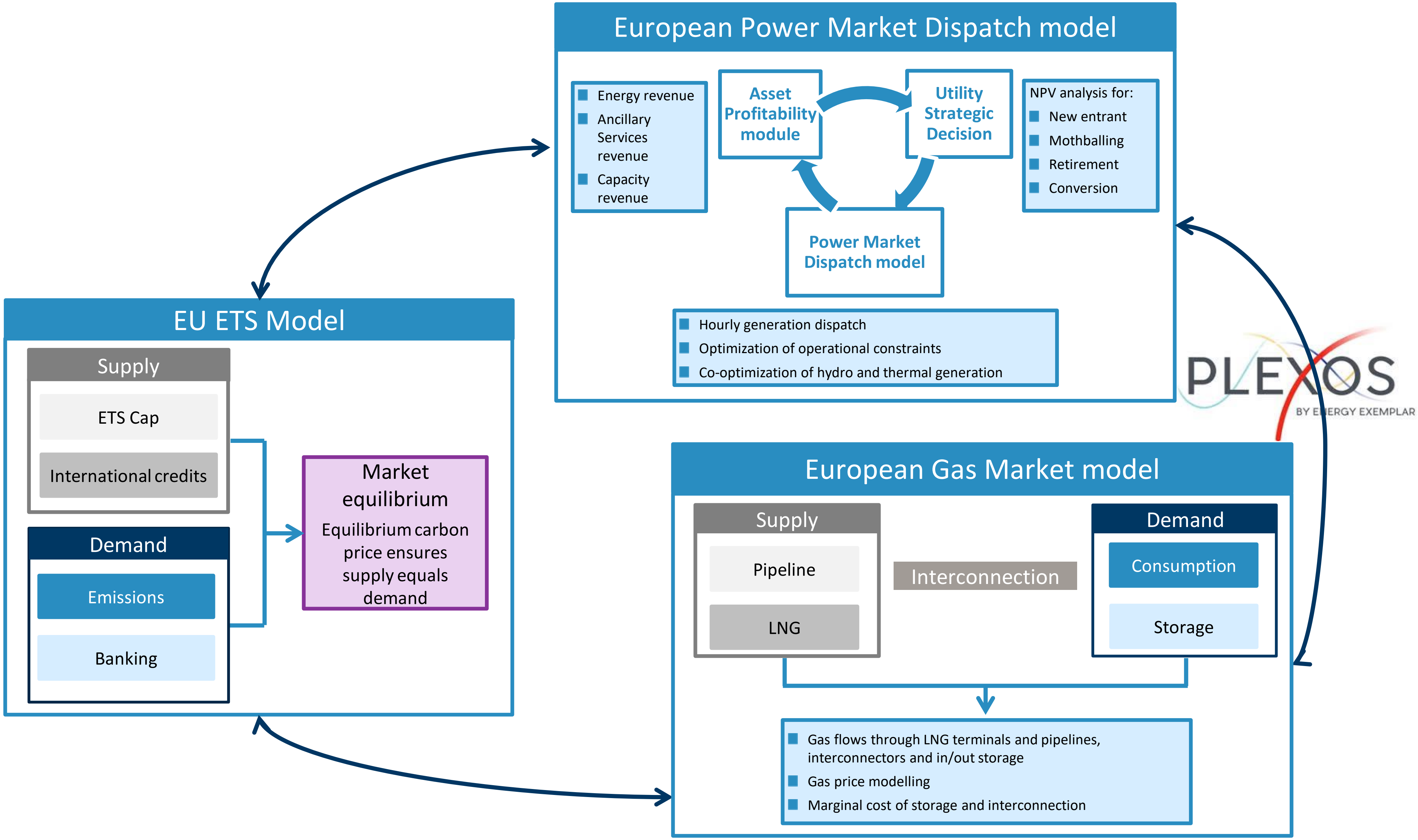
Differences in PM emission estimates derived from the literature between low and high scenarios (kt)



Source: CL Energy modelling

B. CL Energy power market model

FTI-CL energy has developed integrated proprietary models of electricity, gas and CO_2 markets



FTI-CL european power market dispatch model covers all european power markets

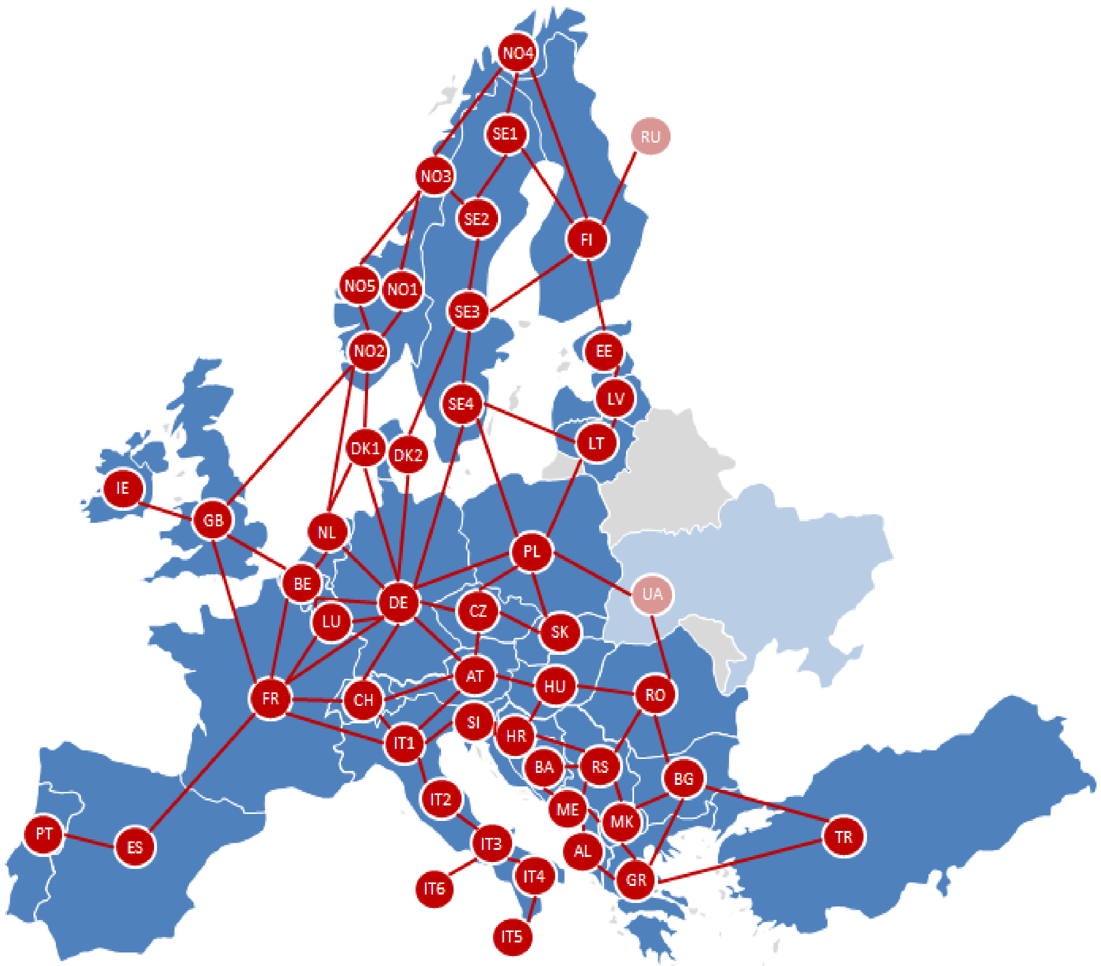
Overview of FTI-CL Energy's power market model

- GB and Ireland
- France, Germany, Belgium, Switzerland, Austria and the Netherlands
- Spain, Portugal and Italy
- Nordic countries: Denmark, Norway, Sweden and Finland
- Poland and the Baltic countries
- Eastern Europe and Greece, as well as Turkey

Model structure

- The model constructs supply in each price zone based on individual plants.
- Zonal prices are found as the marginal value of energy accounting for generators' bidding strategies
- Takes into account the cross-border transmission and interconnectors and unit-commitment plant constraints
- The model is run on the commercial modelling platform Plexos® using data and assumptions constructed by FTI-CL Energy

Geographic scope of the model

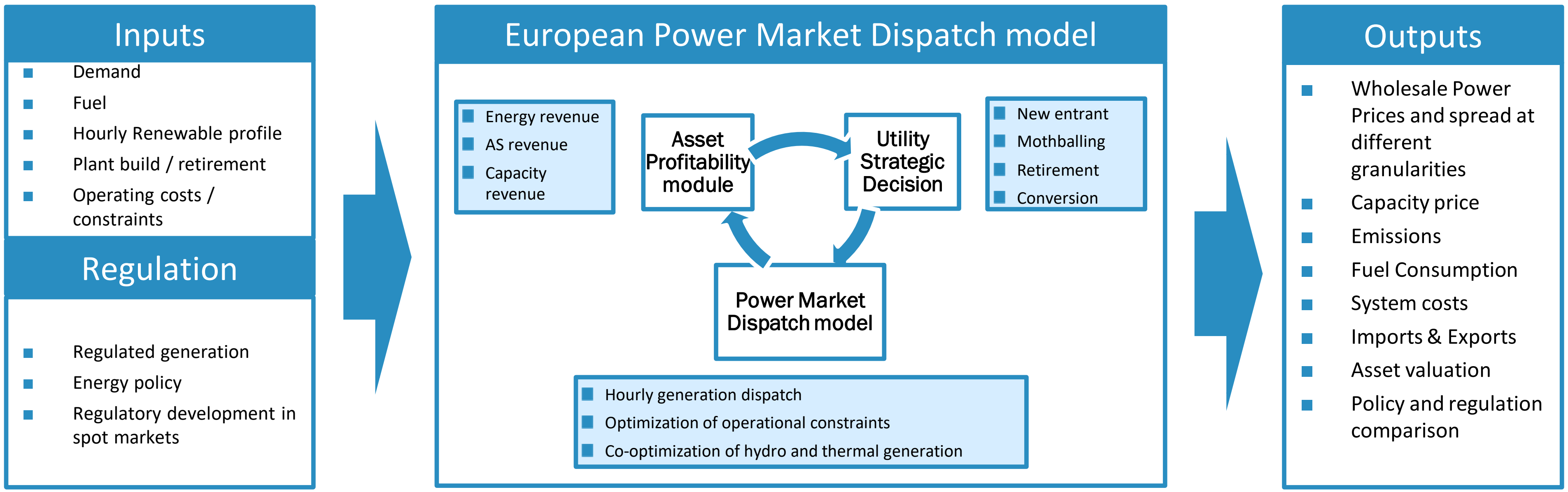


FTI-CL energy's power market model relies on a dispatch optimisation software with detailed representation of market fundamentals

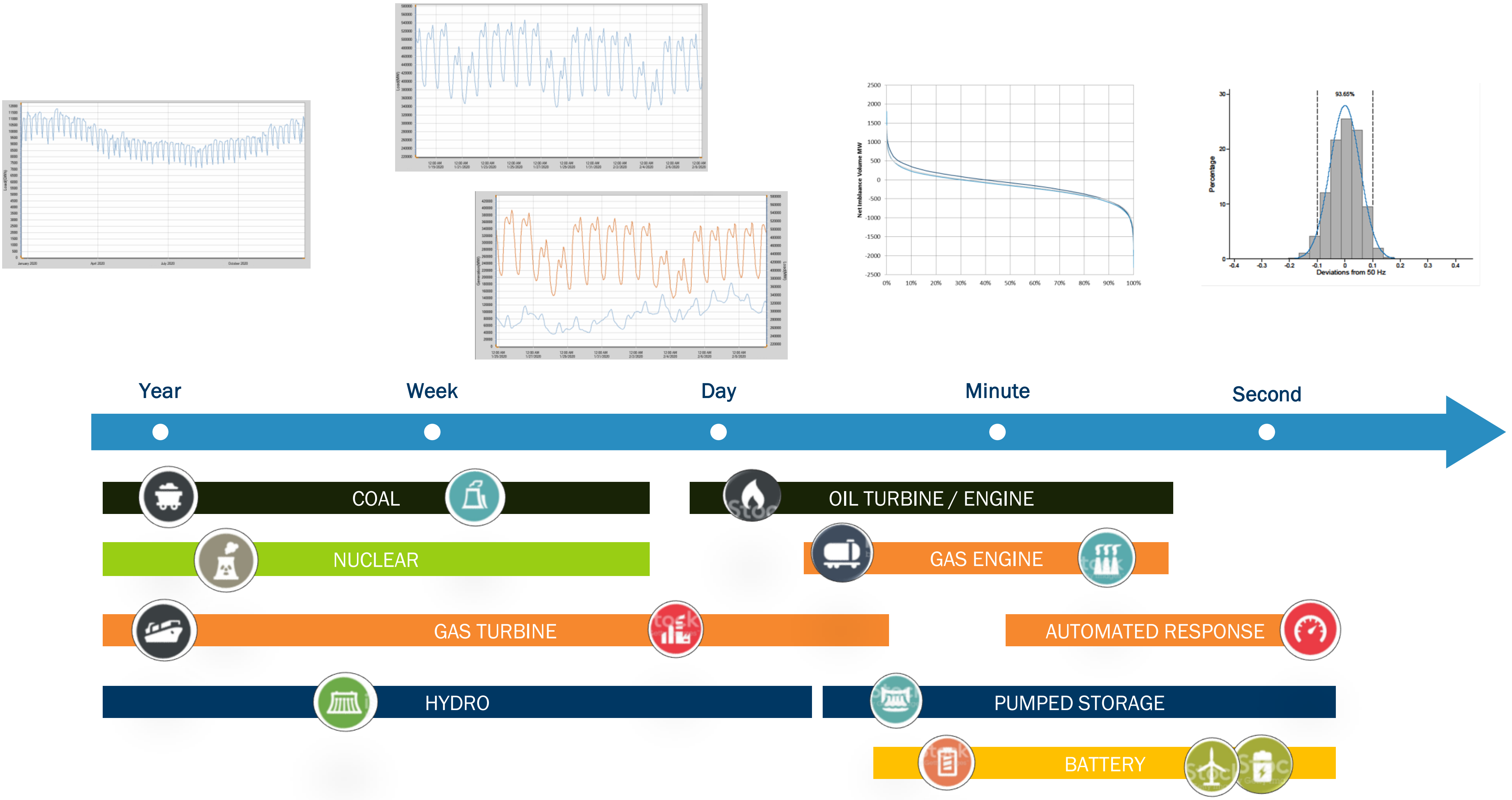
Dispatch optimisation based on detailed representation of power market fundamentals

- At the heart of FTI-CL Energy's market modelling capability lies a dispatch optimisation software, Plexos®, based on a detailed representation of market supply and demand fundamentals at an hourly granularity. Plexos® is globally used by regulators, TSOs, and power market participants.
- FTI-CL Energy's power market model is specifically designed to model renewable generation:
  - Wind: Hourly profiles are derived from our in-house methodology that converts consolidated wind speeds into power output.
  - Solar: Hourly profiles are derived from our in-house methodology that converts solar radiation into power output.
  - Hydro: Weekly natural inflows are derived from our in-house methodology that convert rainfall, ice-melt and hydrological drainage basin into energy. Generation is derived from a state-of-the-art hydro thermal co-optimization algorithm embedded at the heart of Plexos®.

FTI-CL Energy's modelling approach (input, modules and output)



FTI-CL energy's power market suite allows to capture the flexibility and market arbitrage values on short time frames



C. Key modelling assumptions

Key assumptions for power dispatch model

The power market model is set up with a range of inputs derived from latest announcements from TSOS, Regulators and Market Players

Key power price driver	Sources	Optimization
Demand		
Power demand	■ Long term electrification based on EUCO scenarios and Eurelectric	■ Fixed set as demand to be met
Supply		
RES capacity	■ Meet NECPs and EU-wide 60% RES-E penetration share by 2030 ■ CAPEX and OPEX outlook based on latest data from EC and E3M (October 2019)	■ Capacity dynamically optimised thereafter based NPV of anticipated costs and revenues
Nuclear capacity	■ Latest National plans on phase-down or phase-out ■ Latest announcement on plants' life extension and new projects	■ Dispatch optimized by hourly dispatch model
Thermal capacity	■ Latest announcements from operators and National plans on phase-out or conversion to biomass ■ Latest announcement on refurbishment and new projects in the short-term ■ CAPEX and OPEX outlook based on latest data from EC and E3M (October 2019)	■ 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 and E3M (October 2019)	
Commodity prices		
Gas	■ Forwards until 2023, convergence to IEA WEO 2020 Stated Policies by 2030	■ Fixed set as an input (see appendix)
Coal ARA CIF	■ Forwards until 2023, convergence to IEA WEO 2020 Stated Policies by 2030	■ Fixed set as an input (see appendix)
CO2 EUA	■ Forwards until 2023, convergence to EUCO3232.5 in 2030 and 2050	■ Fixed set as an input (see appendix)
Interconnections		
Interconnection	■ ENTSO-E TYNDP 2020 outlook for new and existing interconnections	■ Fixed set as an input (see appendix)

Note: Further details are presented in the Appendixes
(1) MAF: Medium term adequacy forecast; (2) TYNDP: Ten Years Network Development Plan; (3) WEO: International Energy Agency World Energy Outlook

On the demand side, new uses of electricity provide additional flexibility capacity

Power demand modelled flexibility

DSR
- DSR can be activated 40 hours per year

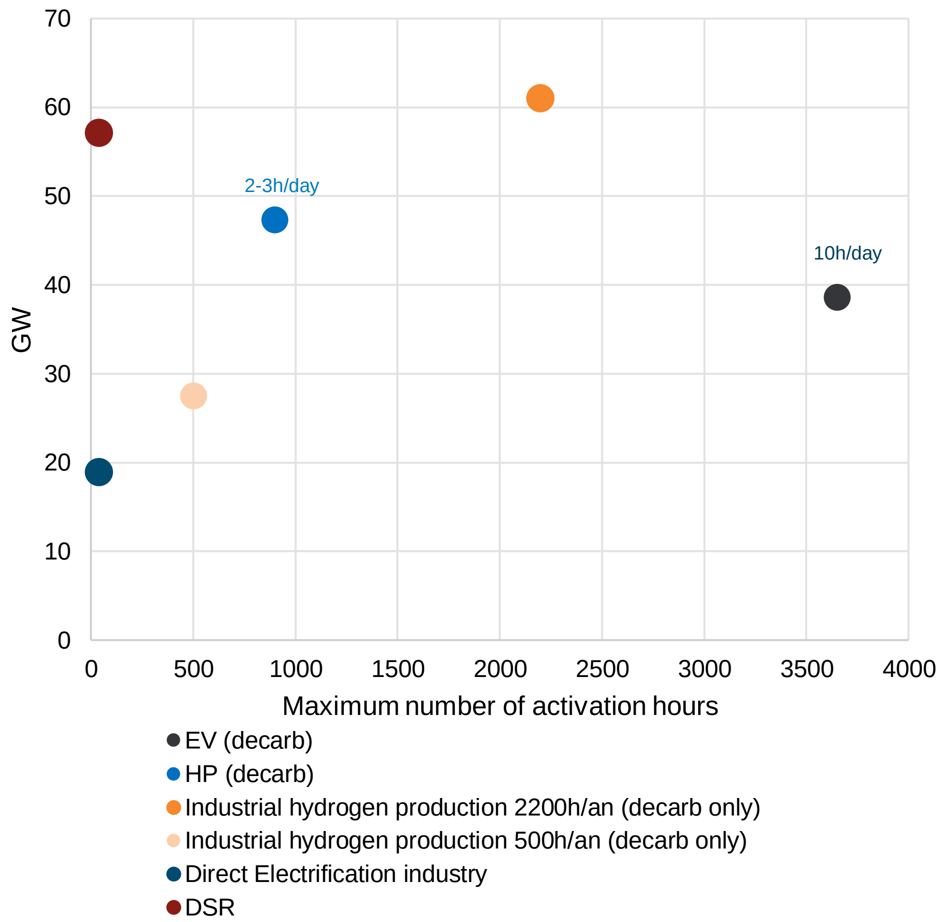
Electric vehicles
- In addition to day/night optimisation, 25% of the vehicles are capable of optimising their load in response to the market price, making possible the modulation of consumption over about ten hours.

Heat pump and cooling
- In addition to day/night optimisation, 50% of the heat pumps are dynamically controlled in response to the market price, making possible the modulate of consumption over 2-3 hours.

Direct Electrification industry
- New industrial electricity demand can be reduced 40 hours per year at 60% of its power

Industrial hydrogen production
To reflect the future potential for flexibility provided by hydrogen production for industry:
- 50% of industrial hydrogen production can be reduced 500 hours per year at 60% of its power.
- 50% of industrial hydrogen production can be stopped 2200h per year

Capacity of demand flexibility in Europe - 2050



The electric vehicle outlook shows a steep increase to 2050 in line with ENTSOE EUCO30 and Eurelectric's latest outlook

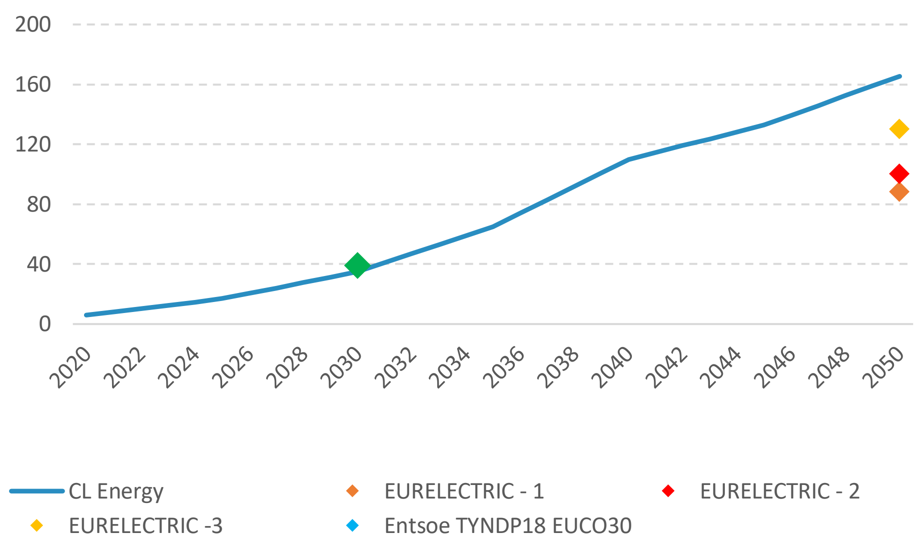
A strong EV deployment generating an important load

- The EV stock grows from 1.6 million in 2020 to **165 million in 2050** or 90% of the total vehicle fleet.
- Our outlook is above the latest EURELECTRIC's high case scenario featuring 130 million EV by 2050.
- It corresponds to a **282 TWh** additional load based on consumption data from ENTSOE.

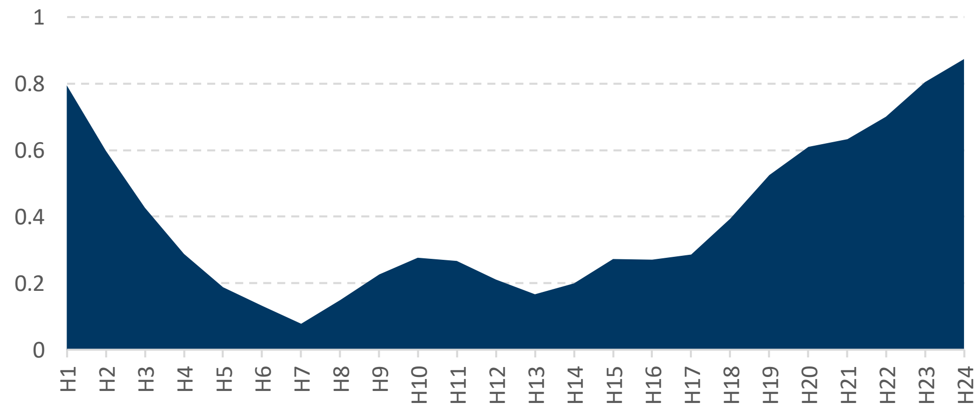
- All EV are assumed to have the same demand profile across EU-27+GB.
  - The default load pattern is based on a day-night load profile and a seasonality factor, provided by ENTSOE.
  - In addition to day/night optimisation, 25% of the vehicles are capable of optimising their load in response to the market price, making possible the modulation of consumption over about ten hours.

We project a high EV deployment throughout EU in line with most recent studies. To reflect future smart charging system, 25% of the EV stock is modelled as responsive to power price.

Number of EV outlook (EU-27+GB, million units)



Hourly load per EV (kW)



Source: CL Energy analysis, Eurelectric, ENTSOE

The heat pump outlook shows a steep increase to 2050 in line with ENTSOE EUCO30 outlook

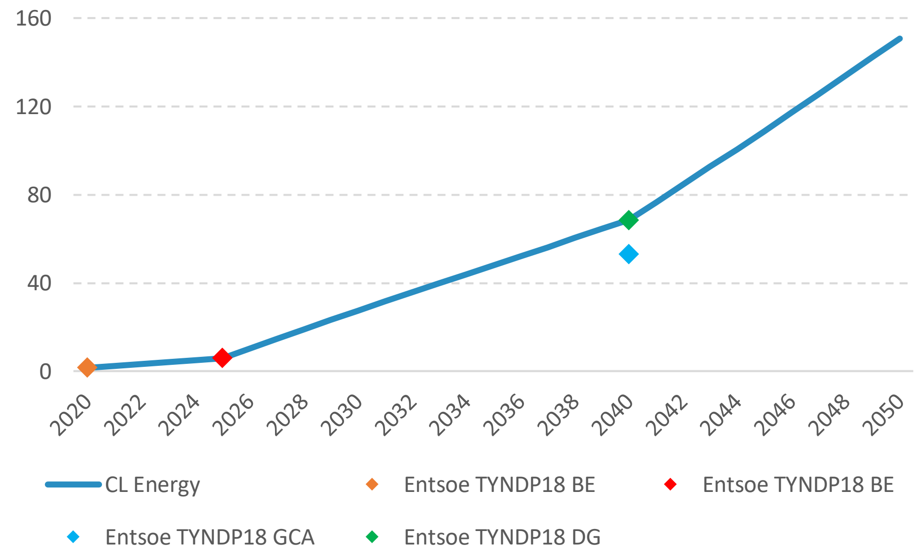
Additional load from increasing number of HP

- The number of heat pumps will increase from about 2 million in 2020 to **150 million in 2050**
- The corresponding additional load based on ENTSOE's consumption data equals **340 TWh.**
- This projection is **in line with ENTSOE**'s between 2020 and 2040.

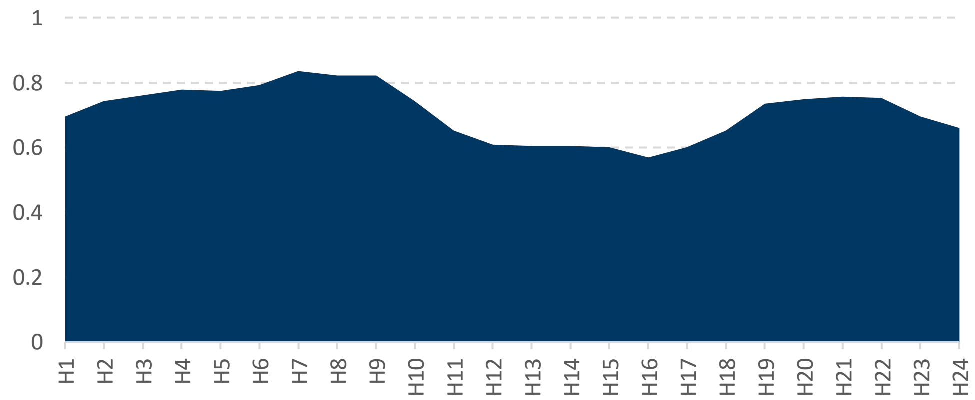
- **HP load curve depends on the country**, each one having different climate conditions and therefore requiring specific heating.
  - HP are considered as changing the shape of the daily load profile. The default load pattern is based on a day-night load profile and a seasonality factor, provided by ENTSOE.
  - In addition to day/night optimisation, 50% of the vehicles are capable of optimising their load in response to the market price, making possible the modulation of consumption over about ten hours.

We project a additional load form HP deployment throughout EU in line with most recent studies. To reflect future smart charging system, half of the HP stock is modelled as responsive to power price.

Number of HP outlook (EU-27+GB, million units)



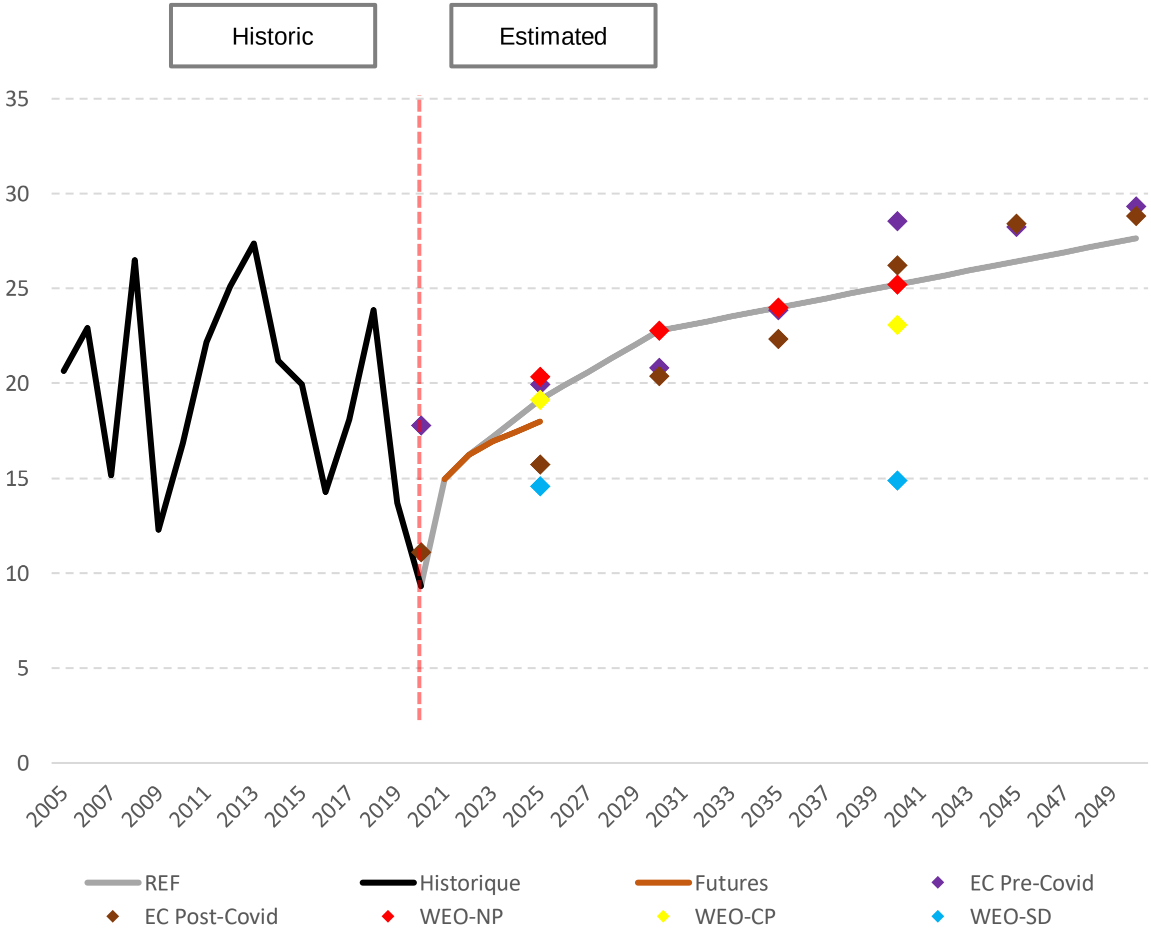
Hourly load per HP (kW)



Source: CL Energy analysis, Eurelectric, ENTSOE

Gas price is assumed to recover from current low levels and converge to WEO NP scenario in line with EC scenarios

Gas price outlook (€2019/MWh)



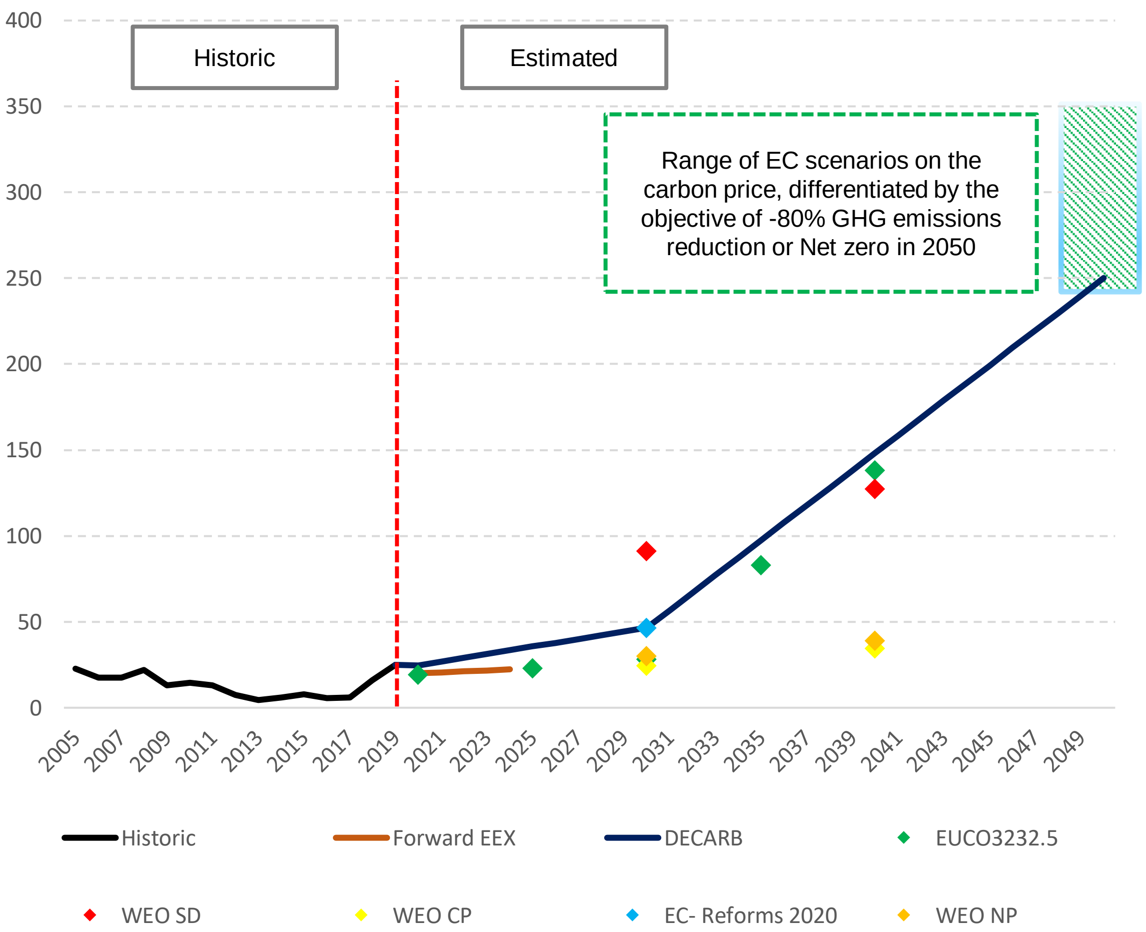
- The high volatility of European gas prices over the last couple of years reflects the numerous uncertainties in the European and global gas markets.
- **Uncertainties are expected to continue** due to:
  - The levels of LNG flows choosing Europe over Asia
    - Higher demand in Asia will push prices up in Europe
  - The levels of power coal to gas switching in Europe
    - Higher use of gas (instead of coal) will increase demand and thus prices
  - The levels of Russian flows to Europe
    - If Russia decides to increase its exports to Europe, it will tend to reduce European prices
- These different drivers will impact European gas prices outlook translating into **different trajectories**. To illustrate this large diversity, we show on the graph the different gas prices projections presented by the IEA on the World Energy Outlook
- The same level of uncertainties is visible **on the coal prices driven by the Asian demand and the level of supply**.

Important uncertainties on Europe gas prices are driven by fundamental drivers such as LNG and Russian imports as well as global demand after the Covid-19 crisis.

Source: CL Energy based on Bloomberg and IEA World Energy Outlook

CO2 price is assumed to keep increasing to reflect the future ETS reforms by 2030 and increased ambition by 2050

CO2 EU ETS outlook (€2019/tCO2)



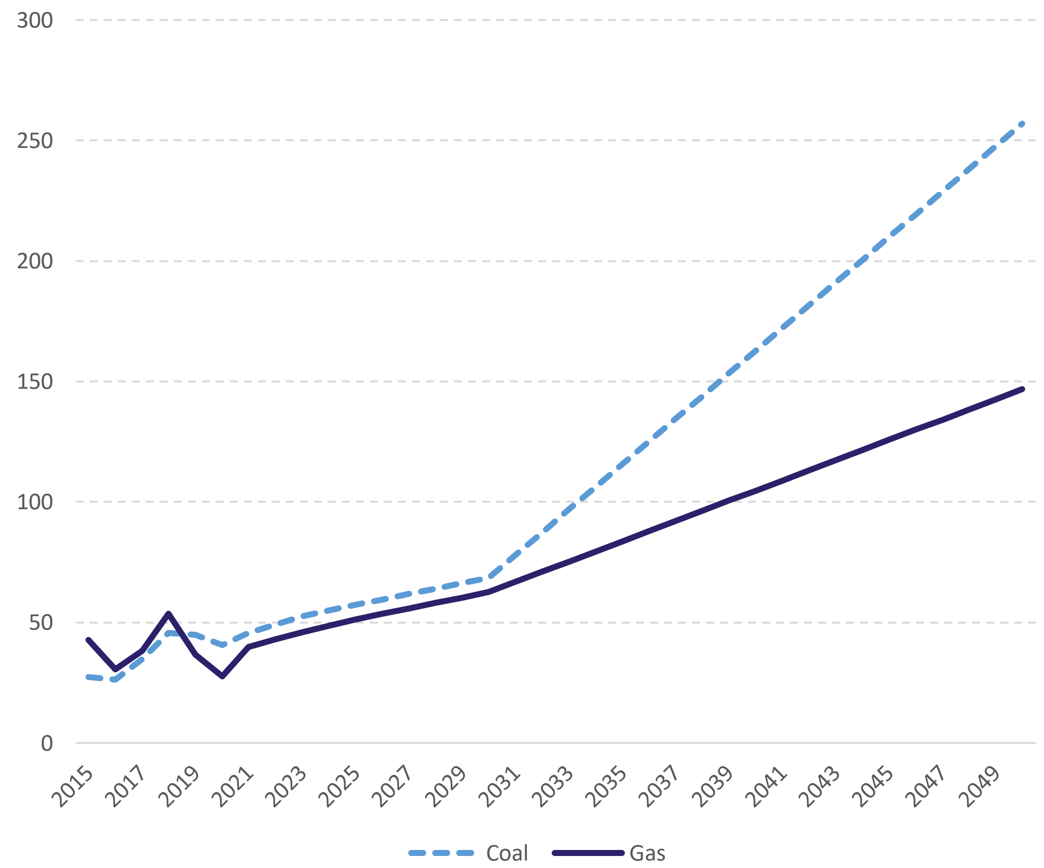
- In February 2018, the approval of the EU ETS reform pushed prices to higher levels. Market is currently trading at ~20€/t. This reforms aim at reducing the current surplus of emission allowances in the EU ETS market.
- Despite this new reform, **important uncertainties remain** regarding the level of carbon prices, driven by:
  - Overlapping policies with the EU ETS market : energy efficiency, renewable generation, coal phase-out …
  - Economic development
  - Decarbonisation objectives
  - EU ETS rules in the long term
- These uncertainties are illustrated by the different scenarios provided by the IEA and EC as shown on the figure.
- To reflect the EC objective to keep the EU ETS as a policy tool to drive the decarbonation, the EU ETS outlook follows EC decarbonisation scenarios using EC Reform 2020 in 2030 and decarbonisation scenario range in 2050.
- In the UK, the CPF is assumed to be maintained at c45€/t until EU ETS increases beyond this threshold in the early 2030s

Despite a recent rebound due to the 2018 EU ETS reforms, the carbon price outlooks remain difficult to determinate due to uncertainties about the installed capacity, demand and long term objectives as well as the post Covid-19 crisis. To reflect EC objective, EU ETS outlook follows EC decarbonisation scenario.

Source: CL Energy based on Bloomberg, EC outlook and IEA World Energy Outlook

SRMC outlooks show that coal and gas spread remains in line until 2030 before diverging as the CO2 price increases

CL Energy's coal and CCGT SRMCs outlook to 2050 (€2019/MWh)



Source:CL Energy based on Bloomberg and IEA World Energy Outlook

Note: CCGT HHV efficiency: 50%; gas carbon content: 0.183kg/kWh
Coal HHV efficiency: 36%; coal carbon content: 0.336kg/kWh

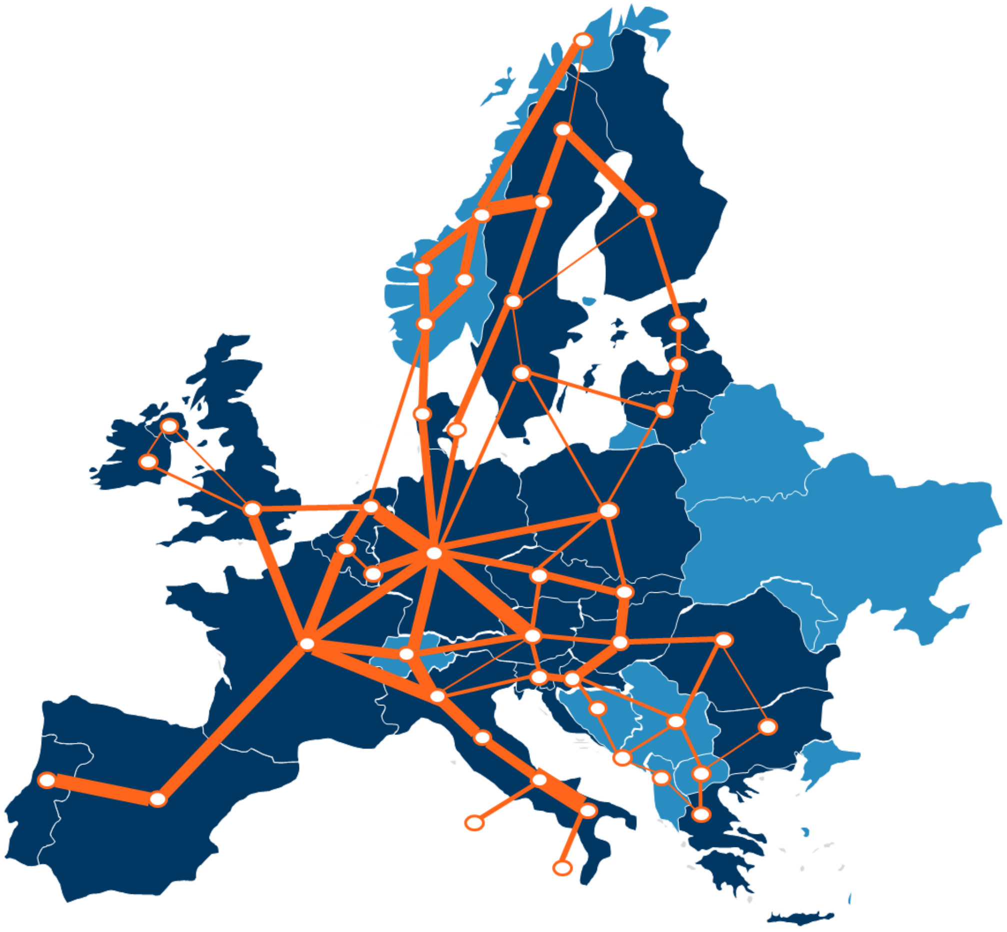
Sharp increase in coal SRMC resulting from high CO2 prices

- The commodity prices assumptions presented above can be summarised in the form of Short-Run Marginal Costs (SRMC), which show the relative competitiveness of coal and gas-fired plants based on their generation costs and therefore impacts the dispatch level of the plant.
- In the medium term, **coal and CCGT SRMCs are likely to continuously increase** due to the commodity markets' rebalancing and the positive impact of envisaged EU ETS reforms on CO2 prices.
- From 2030, as CO2 price increases sharply, **coal SRMC increases to a further extend than gas SRMC leading** materially impacting their competitiveness and their generation level.

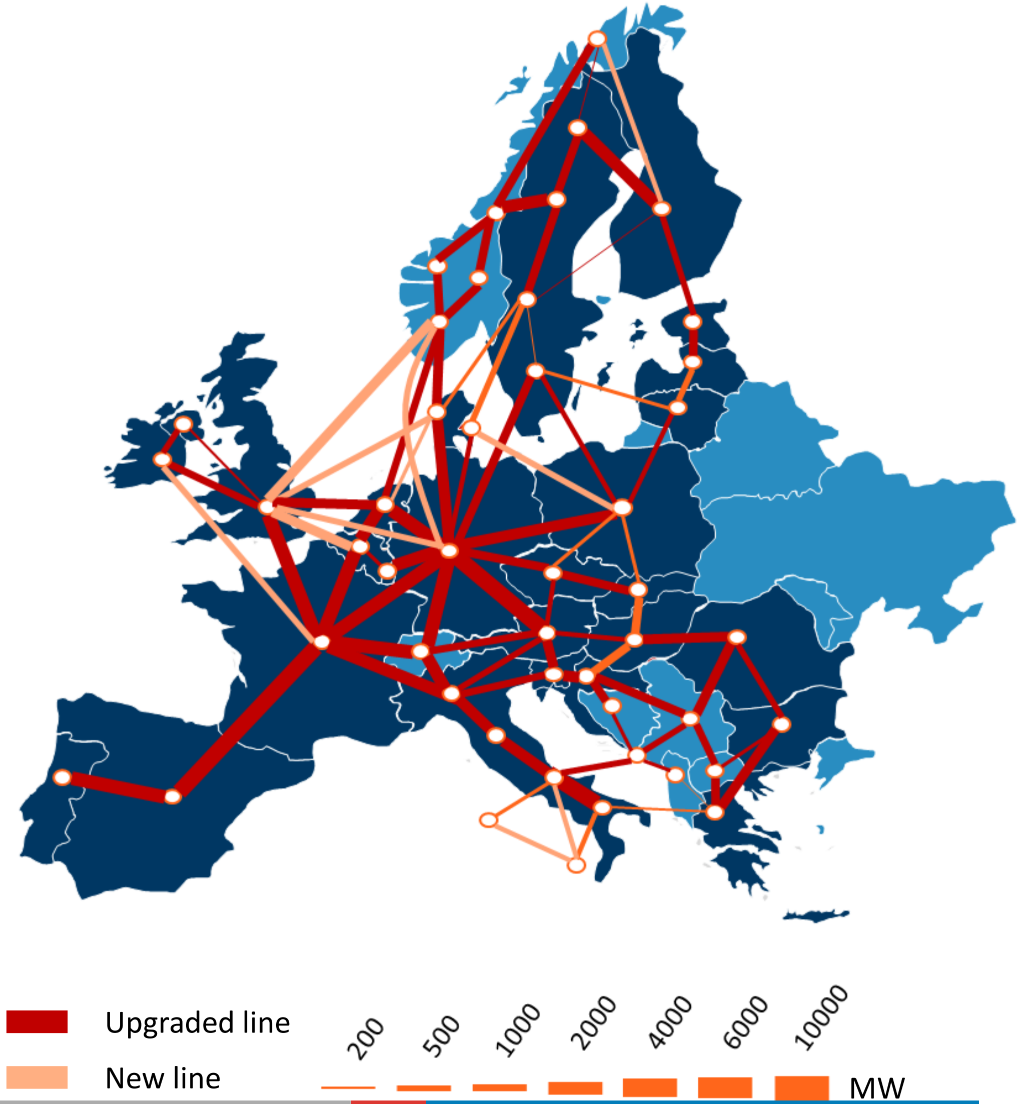
Note: Due to multiple national coal phase-out plans in Europe, the competitiveness of fuels does not drive alone the dispatch of these technology in the mix

Our interconnection NTC development is based on ENTSOE TYNDP 2020 development plan featuring a doubling of NTC by 2050

Network in 2015 **NTC: 225 GW**



Network in 2050 **NTC: 439 GW**



Note: NTC stands for Net Transfer Capacity

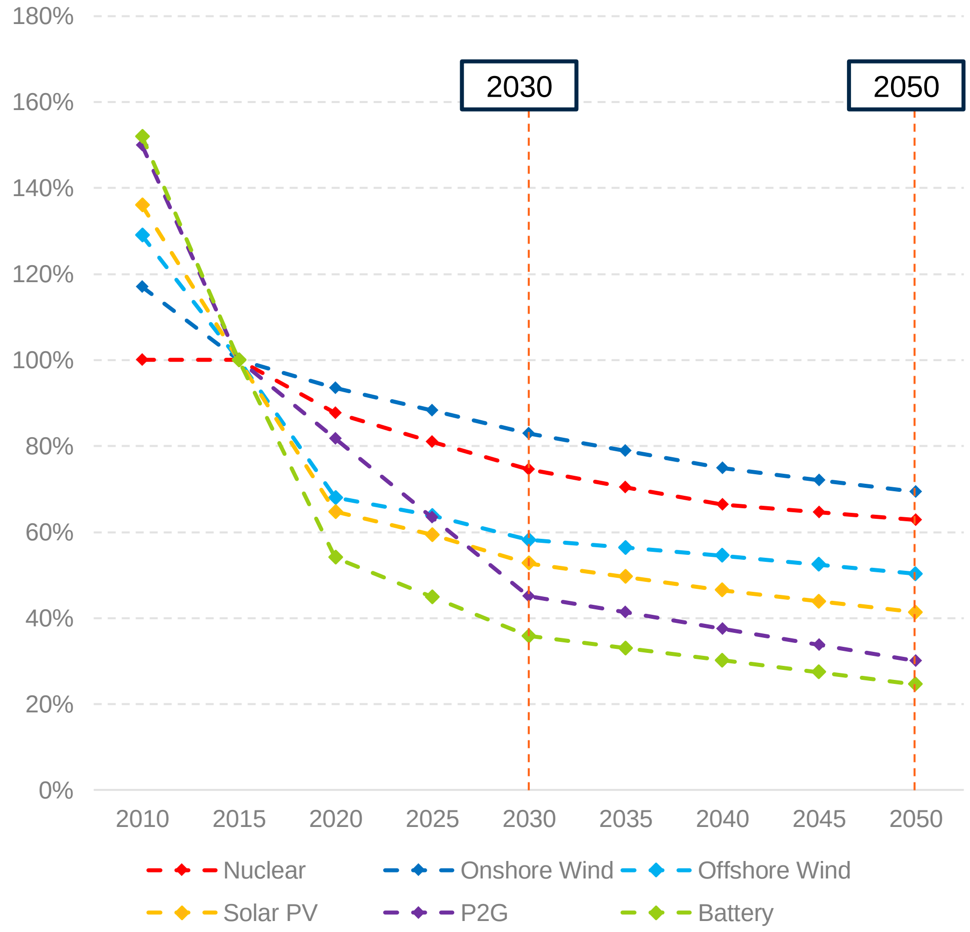
Renewable technologies and storage technologies CAPEX outlook assume a steep reduction by 2030 thanks to further learning effect

RES and storage cost assumptions are based on E3M assumptions resulting from European wide consultation

- In the process of designing the new 2050 energy roadmap, the Commission has set up a market wide review of technology cost outlook to ensure their robustness and representativeness of the current projects.
- Amongst other feedbacks received, the updated E3M technology cost outlooks reflect the latest expectation from market participants and developers of future cost reduction.

% reduction compared to 2015	2030	2050
Nuclear	25%	37%
Wind onshore	17%	31%
Wind offshore	42%	50%
Solar PV	47%	59%
Power to gas	55%	70%
Battery	64%	75%

RES and storage cost reduction (%)



Source: CL Energy, E3M

RES and batteries improvement and expected cost reduction would be due to learning effects in several domains

- Solar panels cost standardization through Europe.
- Reduction in supply chain margins following increasing competition.
- Further technological improvement following historical learning rates.

- Wind turbines improvements implying better capacity factors, especially at low wind speeds.
- Better identification of wind resources further improving wind turbines capacity factor.
- Improvement in components reliability reducing FO&M.

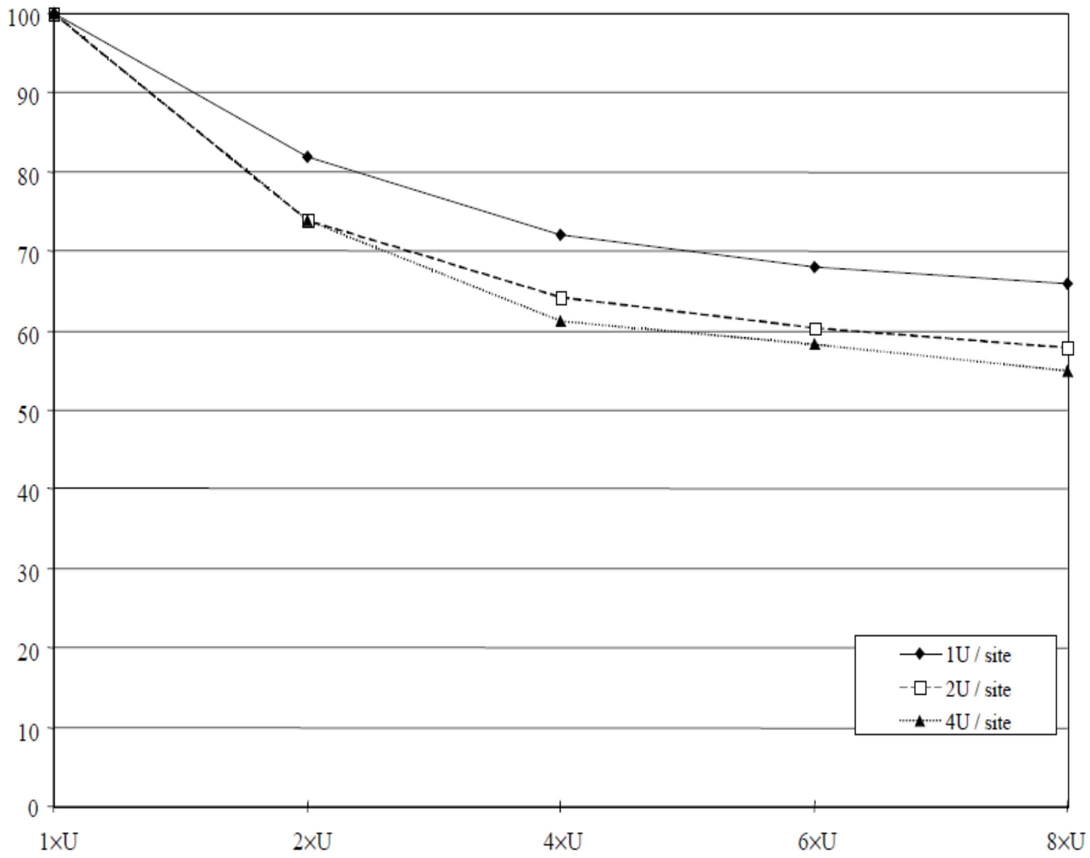
- Intense competition provoking several disruptions in the market including new chemistries development.
- Convergence toward production best practices.

Similarly, to other technologies, new nuclear units' costs would benefit from learning and previous experiences

Nuclear cost assumption is based on a learning curve derived from existing literature

- The learning rate of nuclear costs in this study is adapted from literature[1], assuming a pace of at least one build every 5 years and a standardization of the technologies at stake.
- The learning curve decreases to 63% of the initial price thanks to a substantial reduction of the construction period, inducing a reduction of the overnight costs and the time related costs.
- The starting point in 2015 is calibrated on latest European projects.
- The cost for nuclear plants' long term operation (LTO) is calculated based on European Commission communications[2] assuming a 10 year duration of these life extensions.

Average cost of one unit in a programme of n units[1]



Sources: OECD NEA (2000), European Commission (2016)

[1]Reduction of Capital Costs of Nuclear Power Plants, OECD NEA (2000)

[2]Nuclear Illustrative Programme, SWD(2016) 102 final, European Commission

Additionally to modelling European power markets, indirect impacts are assessed based on a thorough literature review

The **Assessment of the two scenarios** on **security, economic** and **sustainability criteria** derived from outputs of the European power market modelling was complemented with qualitative assessment of indirect costs related to air & water pollution, Transmission & Distribution grid development, land use and employment.

Key power price driver	Description	Sources
Security criteria		
Additional T&D infrastructure cost	How would the need for additional infrastructure (e.g. gas and power transmission) evolve on EU and national levels?	■ 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?	■ NEA, The Full Costs of Electricity Provision (2018) ■ Delarue et al. (2016) ■ AGORA (2015) ■ Hirth et al. (2013 & 2015) ■ Holttinen et al. (2011 & 2013)
Sustainable criteria		
Air and water pollution	How would Air and Water pollution change depending on nuclear contribution to decarbonisation?	■ European CASES Projects ■ Masanet et al., 2013
Land use	How would Land Use by the power sector change depending on nuclear contribution to decarbonisation?	■ Fthenakis and Kim (2009).
Economic criteria		
Employment	How would Employment in the power sector change depending on nuclear contribution to decarbonisation?	■ OECD/IAEA (2018) ■ Deloitte,Economic and social impact report (2019)

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