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ENERGY

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

Final report

19 November 2018

Presented To: FORATOM
THE VOICE OF THE EUROPEAN NUCLEAR INDUSTRY

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Study context and FTI-Cl Energy mandate

- The European Parliament has reaffirmed its commitment to decarbonise its economy with the ratification of the Paris agreement on 5 October 2016:

"***The European Union turned climate ambition into climate action […] Today we continued to show leadership and prove that, together, the European Union can deliver***" (Jean Claude Juncker, 5 October 2016).

- A number of recent studies from the European Commission (1), the IPCC (2) and various stakeholders (3) have explored the **potential for increased ambition for the decarbonisation of the power sector:**
  - These studies suggest a growing role of electricity, from c20% of the European final energy consumption in 2015 to more than 40% by 2050 through electrification of transport, heating and cooling and industrial processes.

- This **creates new challenges and opportunities for the power system** and highlights the need for further modelling of the ways in which the **power sector can meet this increased ambition whilst ensuring security of supply at the least cost for the customer**.

- Furthermore, the latest IPCC (2) report stresses the urgency of the worldwide climate situation and **confirms the need for low-carbon nuclear to tackle climate change**.

- With this background in mind, FORATOM has mandated FTI-CL Energy to analyse what could be **the contribution of nuclear generation towards a low-carbon European economy** in different scenarios regarding nuclear installed capacity, with a specific focus on the **timing and extent of nuclear plants phase-out, life extensions, and new build**.

(1): 2050 EU Energy roadmap (2010), EU Reference scenario 2013, 2016, PINC

(2): IPCC: Global Warming of 1.5C, October 2018

(3): World Energy Outlook (IEA, 2017)

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

Policy objectives

Decarbonisation and sustainability

Security of supply

Affordability /competitiveness

Key research questions

Can a 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 a 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?

- The Vision 2050 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.

We assess three nuclear scenarios using a multi criteria analysis based on quantitative modelling and a literature review

Three nuclear scenarios 2020-2050

- Low scenario
- Medium scenario
- High scenario

Impact assessment based on multi criteria analysis

European Power Market Dispatch Model	Literature review
Capacity requirements and security of supply	Job impact
Generation outlook	Transmission and Distribution cost
Storage requirements and curtailed energy	Balancing cost
Nuclear capacity factor	Land use
Fossil fuel consumption	SO2 emission
CO2 emissions	NOx emission
Power prices	Particular Matter emission
Customer cost	
Investment cost	

Key findings and policy recommendations

Content of the report

1 Key findings

Nuclear contributes to ensuring security of supply

- **In the short to medium term (before 2030),** the lack of commercial maturity of storage technologies implies that **managing the pace of controllable technologies phase-out** (including both fossil plants and nuclear plants) **is necessary to avoid having to extend the life and invest in thermal peaking capacity :**
  - Anticipated nuclear closure (Low scenario) would lead to 20GW of new thermal capacity by 2030, which would become lock-in in the long term;
  - Anticipated nuclear closure (Low scenario) would require extending the life of 7GW of high carbon thermal plants.

- **In the longer term**, with the increased penetration of variable renewable generation, **the European power system will face a growing need for flexibility** – both **short term flexibility** to balance the power system close to real-time and **weekly or seasonal flexibility**. While new storage technologies are expected to see significant cost reductions, and could address a significant share of the flexibility needs, **low carbon dispatchable generation such as nuclear will have a critical role to provide flexibility**:
  - **Nuclear energy can already provide** flexibility to the power system as per the French nuclear operation;
  - In a **Low nuclear scenario** with significant anticipated nuclear plant closures and limited new investments (Low scenario), **significant additional - yet to be proven - flexible storage capacity** (93 GW) would be needed by 2050 to ensure security of supply, including 31GW Battery and 62GW Power to gas on top of the 425GW necessary in the High scenario;
  - By 2050, **nuclear energy would keep contributing to the short term and long term flexibility** requirement of the power system by delivering, daily flexibility potential (80% of installed capacity) as well as seasonal flexibility generating 20% more power in winter than in summer.

- **In addition, managing the pace of nuclear plant phase-out will be necessary to avoid a significant increase in the energy dependency** to imported fuel of the European economy:
  - Anticipated nuclear closure (Low scenario) would increase fossil fuel consumption (gas and coal) by 6500TWh increasing European fossil fuel dependency equivalent to an increase of 36% of the gas consumption of the power sector over 2020-2050 and an increase of 18% of the coal consumption of the power sector over 2020-2050.

Nuclear contributes to reducing the power system emissions

An efficient and sustainable power sector transition toward low carbon technologies will need to account for **both carbon emissions alongside the transition pathways, as well as other forms of air pollution, impact on land use, and nuclear waste**.

- While all considered scenarios meet the 2030 target and 2050 decarbonisation objective, the **probability to reach the objective is higher in the scenarios featuring at least a stable nuclear share,** as these show less cliff-edge effects in the long run and reduce emissions in the transition in the short and medium term:
  - Anticipated nuclear closure in the Low scenario would increase CO2 emissions from the power sector by 2270Mt or c17% of CO2 emissions over 2020-50, especially in the short to medium term.

- Further to contributing to reducing CO2 emissions of the power sector, **nuclear generation mitigates the environmental footprint of the European power system**, which is important to ensure the wider environmental and social sustainability of the transition. In a scenario featuring extension and new investments in nuclear power (High scenario), compared to a scenario with anticipated closures (Low scenario):
  - Air pollution and water pollution would be reduced by c14%, including a reduction of 15% of SO2, 9% of NOx and 18% of PM; and
  - Land use would be about 15800km2 lower by 2050 – equivalent to half of the area of Belgium – as nuclear generation is more energy intensive than variable RES and fossil fuel;

- Additionally, nuclear power is the only large-scale energy-producing technology that takes full responsibility for all of its waste and fully integrates these costs.
  - The amount of waste generated by nuclear power is very small compared to other electricity generation waste.

Nuclear mitigates the costs associated with the power sector transition

- **The impact of the power sector decarbonisation on costs for consumers would benefit from the future possible cost reductions of different technologies including nuclear, as a results of learning by doing and technology innovations:**
  - We assume that Nuclear CAPEX can decrease by 37% over 2020- 2050, leveraging technological improvements.
  - This compares to 31% / 50% / 59% further cost reduction for wind onshore / offshore / solar over 2020-2050 and 20% reduction during 1980-1990 when building additional nuclear units on same site in France.

- **Over the modelling horizon, further nuclear development (High scenario) would mitigate the impact of the low carbon transition on customer cost by 350bn€ (real 2017) via lower total generation costs:**
  - In the short term, anticipated nuclear closure (Low scenario) would increase EU customer cost by315€ (real 2017) over 2020-35.
  - In the long term, further nuclear development (High scenario) would further reduce EU customer cost by 35bn€ (real 2017) over 2035-50.

- **Furthermore, compared to anticipated nuclear closure (Low scenario), further nuclear development (High scenario) would mitigate network and balancing cost:**
  - Further nuclear development (High scenario) would mitigate network development cost increase by 160bn€ (real 2017) by 2050; and
  - Further nuclear development (High scenario) would mitigate balancing cost increase by 13bn€ (real 2017) by 2050.

- **Nuclear generation would also provide additional benefits to the European economy:**
  - Maintaining nuclear capacity and further new investments would create about 1 million high skilled direct job-years in Europe, from the conception and construction phase to the operational phase.

Conclusions

- **The contribution of nuclear to the transition towards a European decarbonized power system needs to be recognized:**
  - **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

1 Modelling assumptions and scenario definition

A

Modelling approach

Description of the modelling approach

- **The modelling of the three scenarios leverages on FTI-CL Energy in-house European power market model supplemented by a range of additional indicators, and uses the following approach:**

1. **Benchmark of current long term scenarios** with regards to the long term decarbonisation objective.
2. Analysis of the **outlook for power demand** across existing studies presenting decarbonisation pathways for the European economy with significant electrification of the economy and meeting the EC targets for the power sector decarbonisation.
3. Design of **three nuclear installed capacity scenarios (Low / Medium / High)** reflecting different degrees of ambition for the role of nuclear in decarbonising the EU power sector.
4. For each of these three scenarios, European power markets are modelled using FTI-CL power market model:
   - ➢ **Dynamic long term 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 a hourly basis.
5. **Assessment of the three nuclear capacity outlook scenarios** on a number of **security, economic** and **sustainability criteria** derived from outputs of the European power market modelling, complemented with qualitative assessment of indirect costs related to air & water pollution, Transmission & Distribution grid development, land use and employment.

B Modelling assumptions and scenario definition

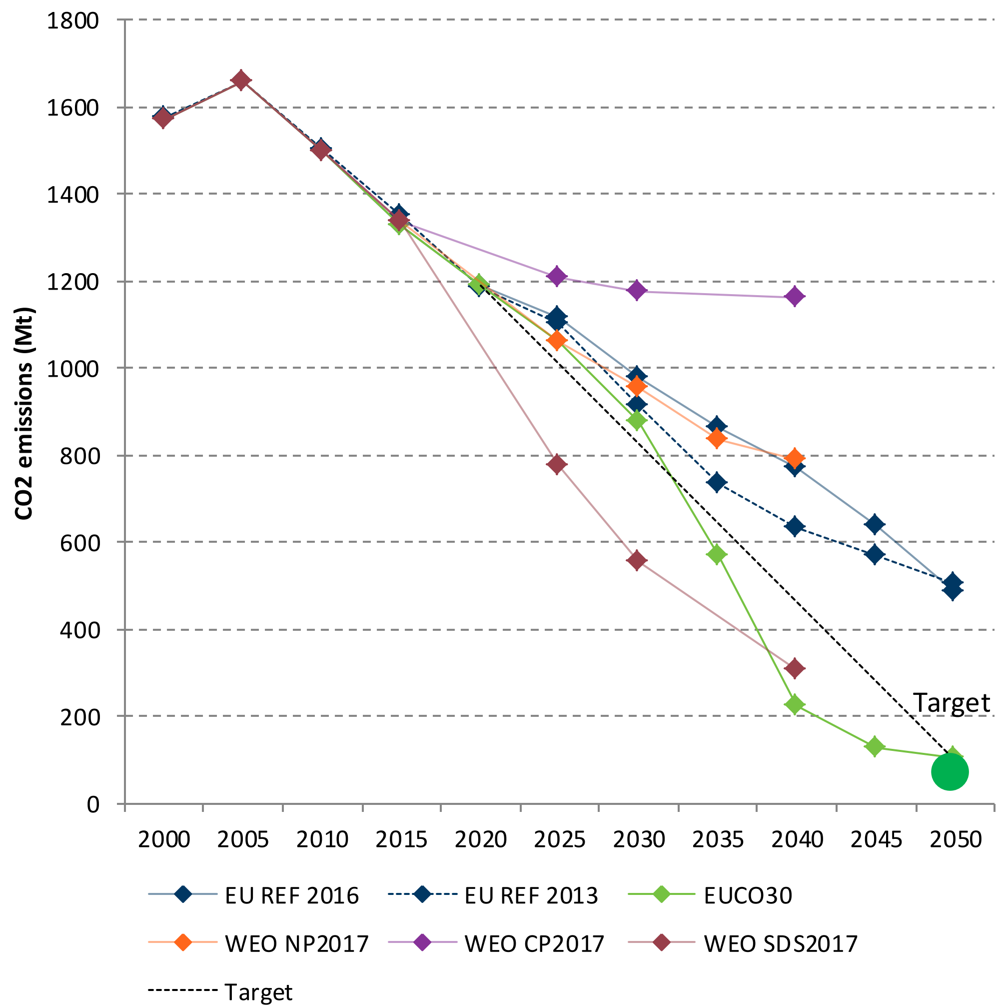
Currently only a few scenarios designed by European or international organisation achieve the decarbonisation objective, …

Long term scenario from EC and IEA

- Currently, only a selected number of scenario designed by the European Commission (EC) and the International Energy Agency (IEA) through the annual World Energy Outlook (WEO) achieve the decarbonisation target set out by the commission.

- As such, as shown on the opposite graph:
  - Two scenarios meet the 2050 decarbonisation objective (EUCO30 and WEO SDS 2017) which both assume a strengthen commitment towards decarbonisation through combination of energy efficiency measures, electrification and low carbon power generation incentives.
  - While the other three scenario (WEO CP2017, EU REF 2016 and WEO NP2017) do not meet the decarbonisation objective as they assume that the current energy policies and commitment will not be sufficient to reach the 2050 target.

CO_2 emissions reduction path in different energy scenarios



Note: IEA CO_2 emission are rescaled to EU28 geographic scope

…, and amongst other proprieties, they all feature a high nuclear share as opposed to current scenarios from system operator.

Nuclear contribution in decarbonisation

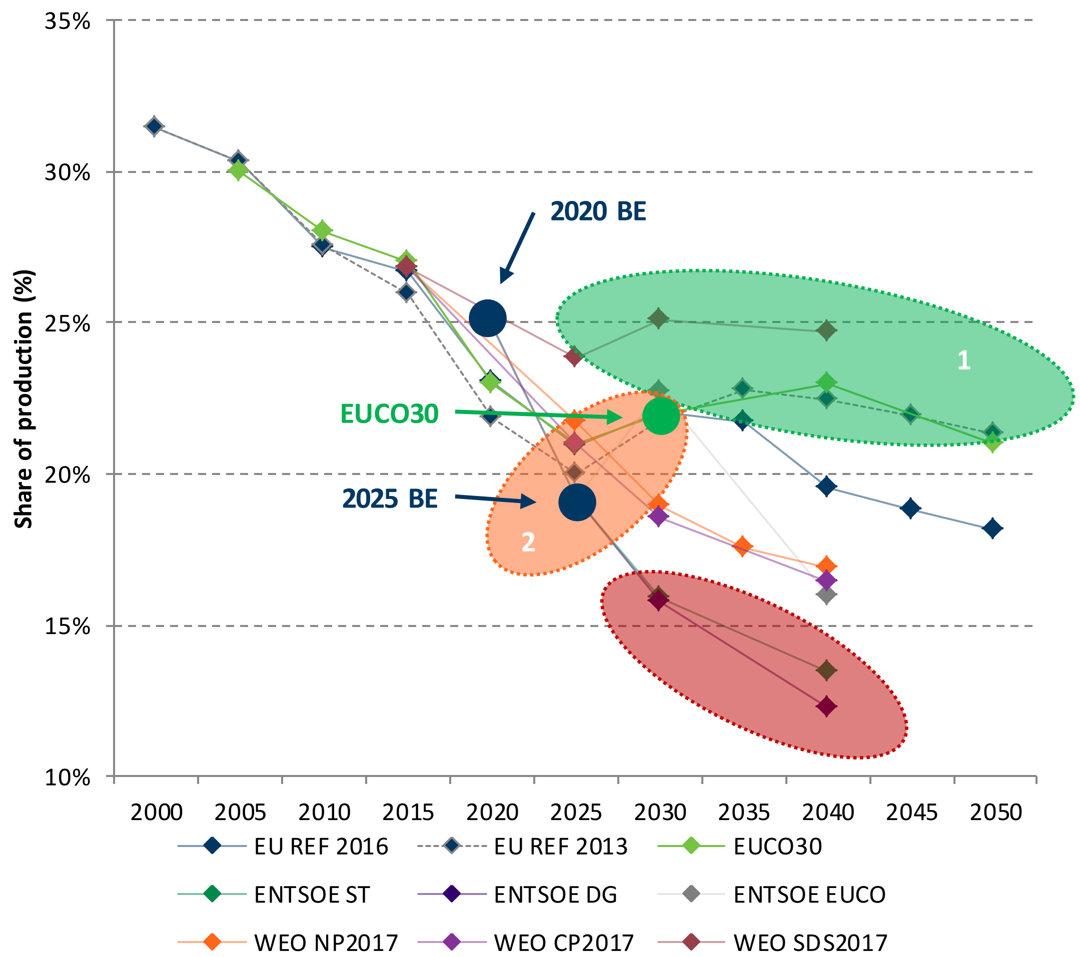
- Within the range of available scenarios that cover long term horizon, we can identify three categories of nuclear scenarios:

1. **High scenarios**
   - High nuclear contribution in WEO SDS and EUCO30 scenarios meeting 2050 objective
2. **Medium scenarios**
   - EUCO30 target is met with a nuclear contribution higher than 2025 Best Estimate contribution
   - c15% of the current installed nuclear capacity.
3. **Low scenarios**
   - Latest scenarios from ENTSOE and TSOs
   - Feature the lowest nuclear contribution

- The high scenario range includes both compliant scenarios outline in previous slide while the low scenario range includes the view from the system operators based on latest energy policies and regulations.

This discrepancy highlights the need to identify the contribution of nuclear to ensure that the transition to decarbonisation would be made at least cost.

Nuclear contribution in long-term scenarios (%)



In this context, Foratom' scenarios are designed to meet the European renewables, GHG emissions and energy efficiency targets

Clean Energy package + COP21 – Objective for 2030

GHG – at least 40% GHG reduction (wrt 1990);

ETS/ESD[1] – 43% GHG emissions reduction in ETS sectors and 30% GHG emissions in effort sharing sectors (wrt 2005)

RES – at least 32% share of RES in final energy consumption or 56% in the power sector

EE[2] – 32.5% primary energy consumption reduction (i.e. achieving 1274Mtoe in 2030) compared to the PRIMES 2007 baseline

Long term European Commission objective for 2050

GHG – at least 85% GHG reduction (wrt 1990);

ETS/ESD – At least 90% GHG emissions reduction in ETS sectors

RES – Growing share to be determined based on meeting GHG and ETS objective

EE – 40% primary energy consumption reduction (i.e. achieving 1130Mtoe in 2050) compared to the PRIMES 2007 baseline for 2030[3]

[1] ESD: Effort Sharing Decision

[2] EE: Energy efficiency

[3] 2050 Energy efficiency is based on EUCO33 reduction of gross and primary European Energy consumption as set out in the PRIMES modelling for the Winter Package presentation dated from 4 sept 2017.

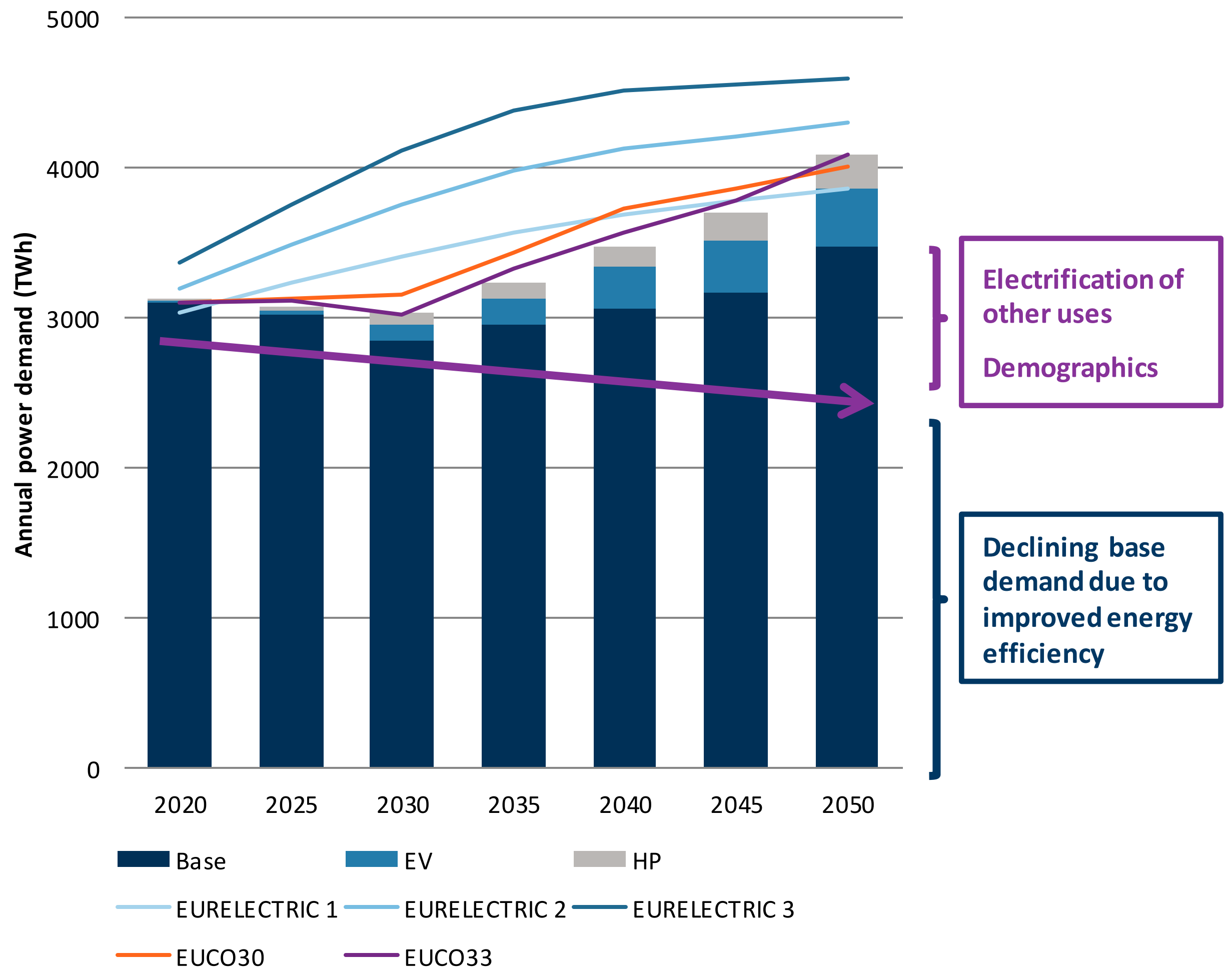
The power demand outlook features high energy efficiency and high electrification, in line with European 2030 and 2050 objectives

Power demand outlook to 2050

- Our demand scenario is designed to replicate **EUCO33*** **outlook total EU28 demand** to **include the latest efficiency targets,** defined by 2030, as well as the **long term electrification** necessary to decarbonise the European economy.
  - It features a **fast EV and HP development** as well as an on-going electrification of other sectors (industry and other transports).
- As a results of these two drivers, European power demand decreases from 3110TWh in 2020 down to 3030TWh in 2030 (-0.02% YoY growth rate); then increases to **4095TWh in 2050** (+1.5% YoY growth rate) with EV and HP accounting for <400TWh and >200TWh respectively.

The power demand outlook captures both energy efficiency measures and future electrification resulting in an increased overall demand in the longer term.

FORATOM's Vision demand outlook compared to benchmarks



Source: FTI-CL Energy, Eurelectric, European Commission

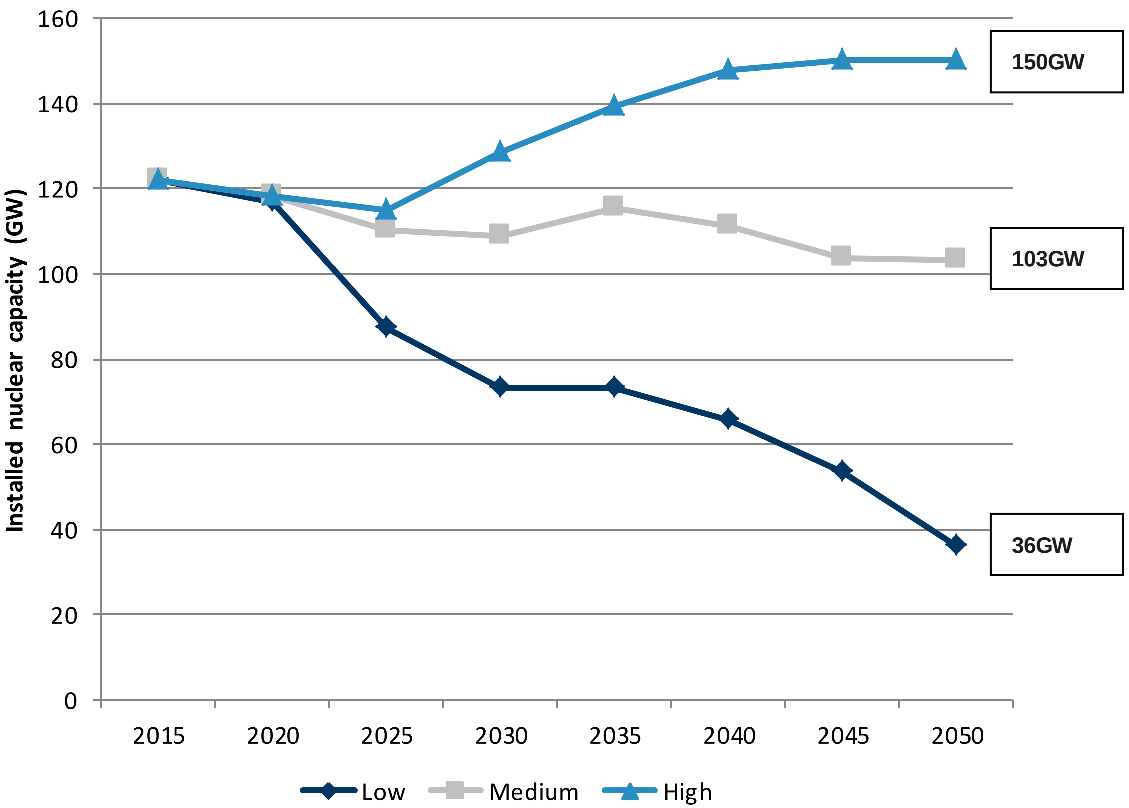
* EUCO33 outlook is the PRIMES sensitivity reaching 33% energy efficiency reduction in 2030 and long term decarbonisation objective developed by E3M with the European Commission.

The nuclear scenarios cover a range of installed capacities reflecting different assumptions for retirements, life extensions and new build

Scenarios design

- Each scenario is based on current nuclear plants and projects under construction as well as planed nuclear phase-down policies. Each scenario then assumes different life extension decisions as well as different commissioning date for future new nuclear plants. As a result:
  - In the **short term**, in all scenarios, nuclear capacity **drops by 5 to 20GW by 2025.**
  - In the **longer-term**, variation of extension and new built decisions lead to the following scenarios:
    - In the **low scenario**, most of the existing plants close without further extensions and new plants projects fail to conclude. The nuclear capacity decreases to **36GW by 2050**.
    - In the **medium scenario**, a number of long term operation (LTO) extensions are awarded and new plants are built, in line with current advanced projects. The nuclear capacity reaches **103GW by 2050**.
    - In the **high scenario**, a number of additional new plants (including c5GW of SMR and <1GW of Gen-IV) are commissioned replacing thermal baseload and contributing to decarbonisation of the power sector and wider European economy. The nuclear capacity reaches **150GW by 2050**.

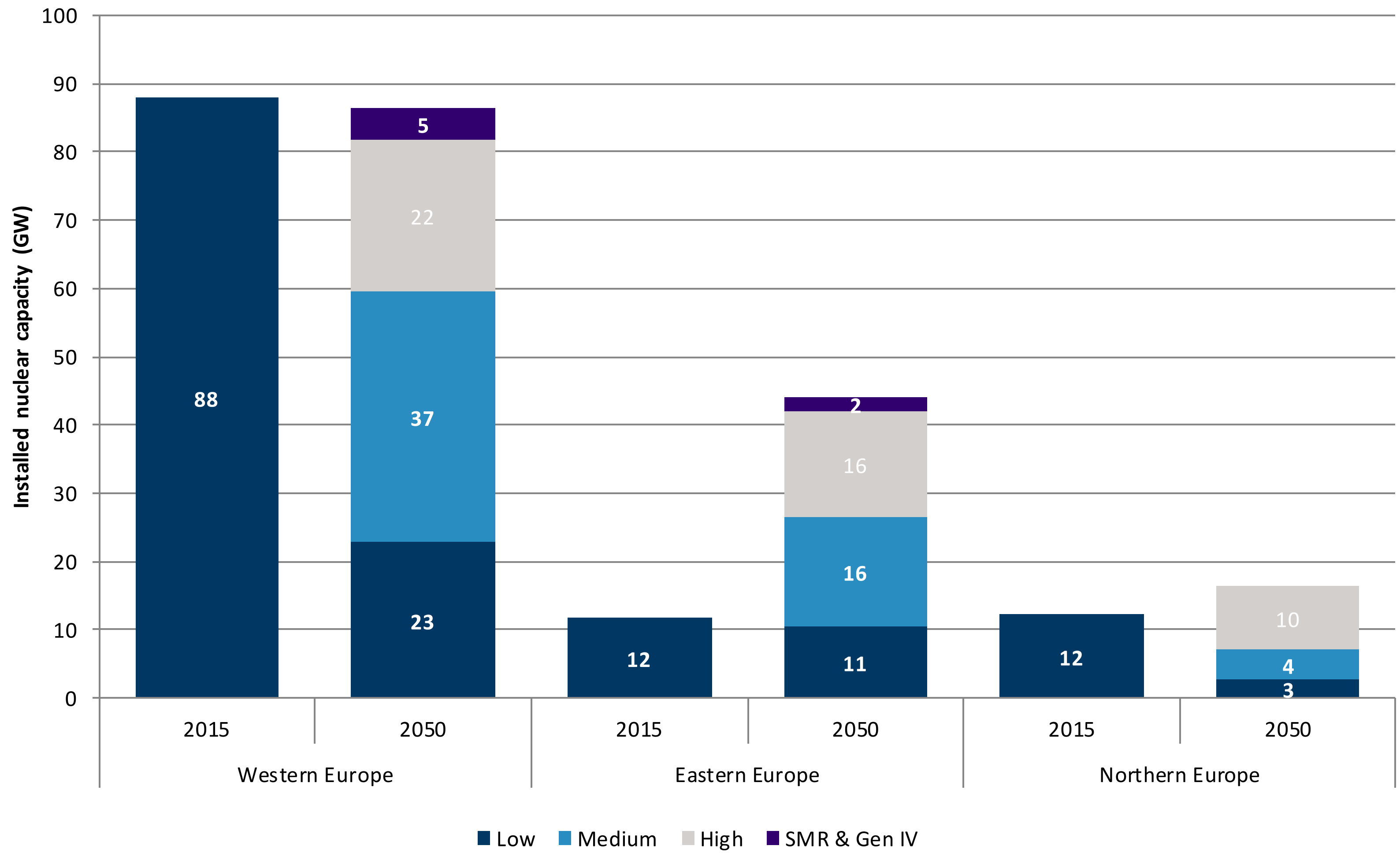
EU-28 nuclear installed capacity outlooks (GW)



Source: FTI-CL Energy analysis based on FORATOM inputs

The nuclear scenarios are derived country by country and reflect different national approaches toward nuclear power

Installed nuclear capacity by region and scenario



Source: FTI-CL Energy analysis based on FORATOM inputs

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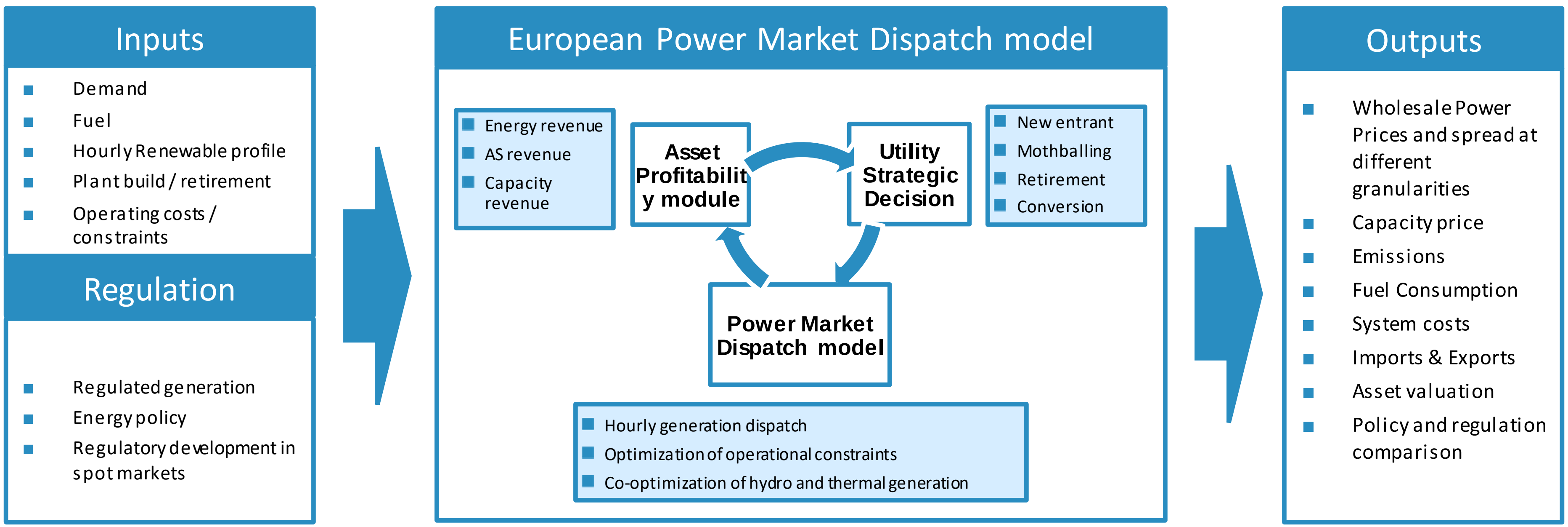
C

European power market model

For each of the three scenarios, European power markets are modelled using FTI-CL power market model

- The **fact-based evidence** in response to the key questions, around the contribution of the European nuclear sector to achieving European energy policy objectives of reliability, decarbonisation and cost efficiency will be analysed using FTI-CL Energy in-house power market modelling environment.
- At the heart of **FTI-CL Energy's market modelling capability** lies a **dispatch optimization 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** and **intertemporal storage problems** with high RES penetration level.
- In order to perform the impact assessment, the EU Power Market Dispatch model is set up to comply with long-term decarbonization objective while using the assumptions described on next slide.

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



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 EU objective of 56% RES-E penetration share by 2030 ■ CAPEX and OPEX outlook based on latest data from EC and E3M (June 2018)	■ 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 (June 2018)	■ 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 (June 2018)	
Commodity prices		
Gas	■ Forwards until 2020, converge to IEA WEO 2017 New Policy by 2025	■ Fixed set as an input (see appendix)
Coal ARA CIF	■ Forwards until 2021, converge to IEA WEO 2017 New Policy by 2025	■ Fixed set as an input (see appendix)
CO2 EUA	■ Forwards until 2021, converge to EUCO33 by 2025, EUCO30 by 2030/35	■ Fixed set as an input (see appendix)
Interconnections		
Interconnection	■ ENTSO-E TYNDP 2018 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

Additionally to modelling European power markets, indirect impacts 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 will be 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, The 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 (2015)

2 Modelling results

A

Power market model results

Power market modelling results

- **Objective:** The power market modelling enables to assess the nuclear contribution to achieving European energy policy objectives of reliability, decarbonisation and cost efficiency by comparing a number of power market modelling outputs.

- **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 CO2 emission;
  - Wholesale power price;
  - Customer cost; and
  - Investment cost

In the medium scenario, RES capacity reaches 1570 GW (+231%) by 2050, while the flexible capacity hits 500 GW (+695%)

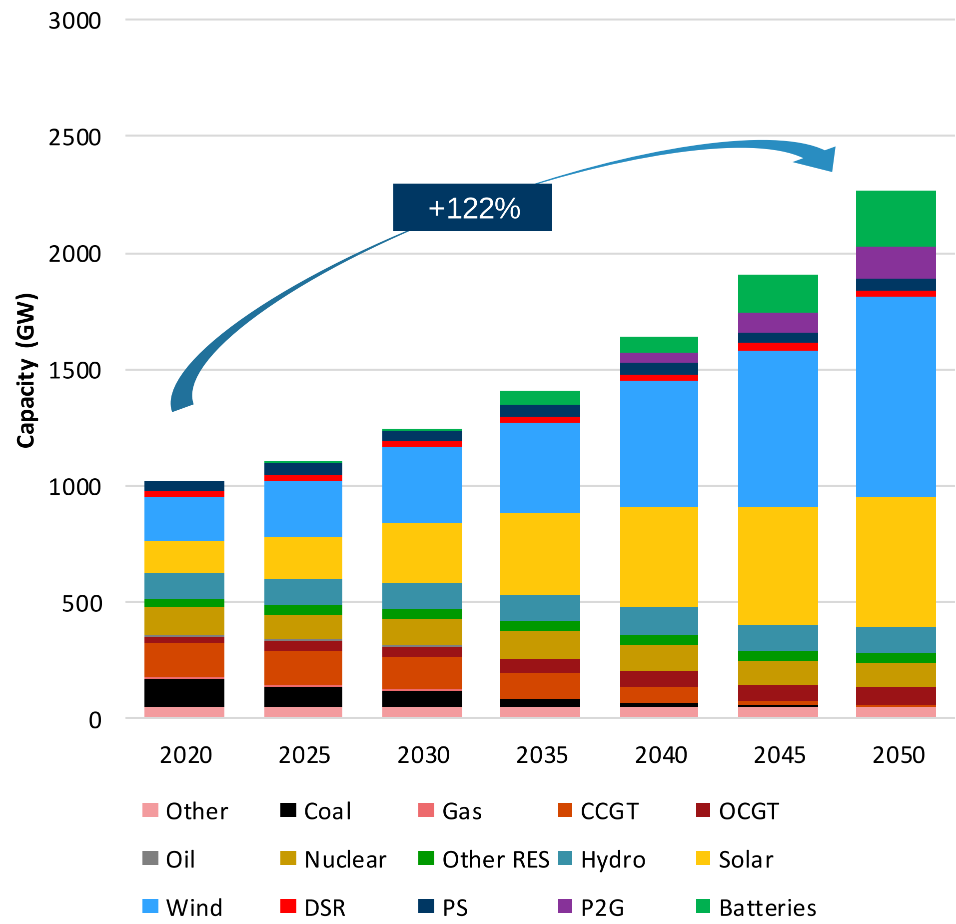
Modelling approach

- The model is set up so that sufficient capacity is operational to ensure security of supply at least cost

Installed capacity outlook:

- **Thermal plant closure**:
  - Between 2020 and 2050, 300GW of the existing 310GW of thermal capacity (97%), would close due to anticipated closure or reaching their end of life.
- **This would be replaced by**:
  - 1100GW of **new RES** over 2020-2050 reaching a total of 1570GW in 2050
    - Wind: 860GW; and
    - Solar: 560GW
  - 445 GW additional **new flexible capacity**:
    - 240GW battery;
    - 5GW DSR*;
    - 55GW thermal peakers; and
    - 145GW Power to Gas**

Medium scenario capacity outlook



Source: FTI-CL Energy modelling

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"

* The study considers that 25GW of DSR would already be operational by 2020

** "Power to Gas" refers to Power-X-Power storage technology

The low scenario features an increase of 535GW to compensate for a reduction of 114GW of nuclear power

Installed capacity outlook in the Low scenario

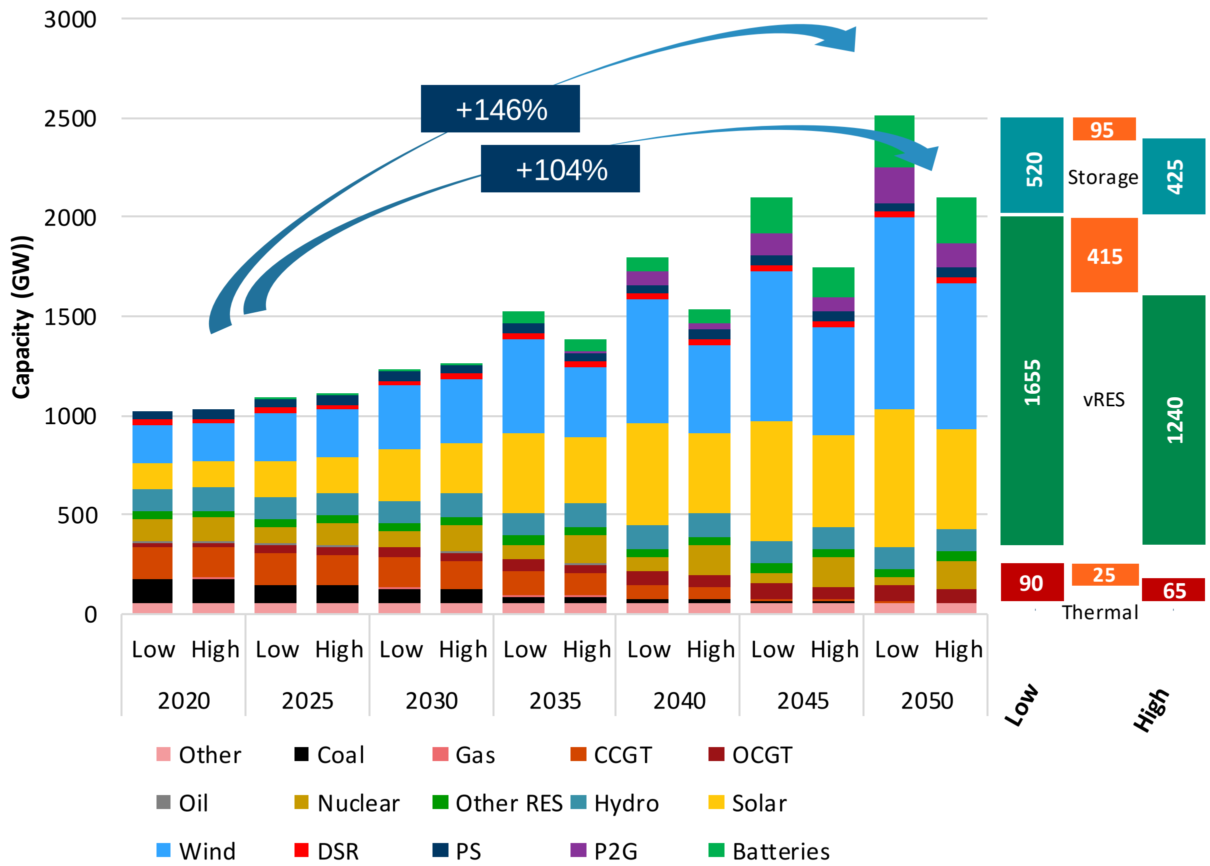
- In the low scenario, 1345GW of new RES are installed reaching a total of 1655GW including 695GW of solar and 960GW of wind.
- Additionally, 520GW of new flexible capacity is installed, of which 265GW of batteries and 180GW of Power to Gas.

Installed capacity outlook in the High scenario

- In the high scenario, 930GW of new RES are installed reaching a total of 1240GW including 505GW of solar and 740GW of wind.
- Additionally, 425GW of new flexible capacity is installed, of which 230GW of batteries and 120GW of Power to gas.

A reduction of 114GW of nuclear in 2050 would therefore lead to an increase of c415GW of RES (190GW of solar and 225GW of wind),c95GW of new storage and c25GW of new thermal.

Low and High scenario capacity outlook



Source: FTI-CL Energy modelling

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”

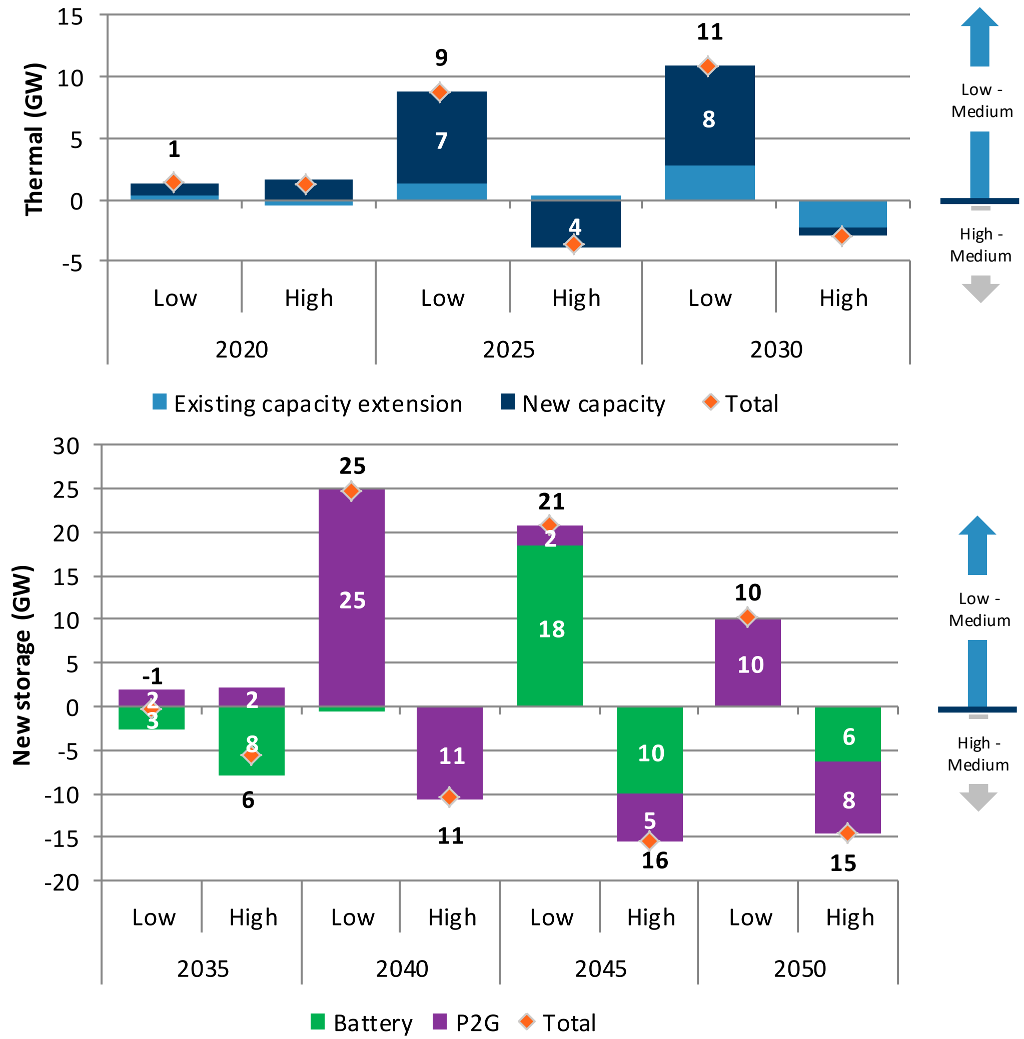
A low nuclear share increases investment in thermal and yet to be proven storage technologies by 128GW to ensure security of supply

Impact of low nuclear scenario vs high nuclear scenario:

- In the short term (to 2030), anticipated closure of nuclear capacity would require about **27GW of additional thermal capacity:**
  - 20GW of new capacity would be built, to ensure security of supply in the short to medium term. These investments would risk becoming stranded in the long run.
  - 7GW of existing carbon intensive units would be extended.
- In the longer term, anticipated nuclear closure and limited new nuclear investments would require about **93GW of additional new investments in flexible resources in 2050** (31GW Battery and 62GW Power to gas):
  - Given that batteries have a 10 years lifetime, implies that c40GW of additional capacity would need to be commissioned between 2035 and 2050 to reach 31GW 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 c36GW would be required before 2040.

A low nuclear generation share would materially increase the reliance of the long term power system on storage technologies which are yet to be proven as soon as 2040.

Additional new capacity compared to medium scenario



Note: comparison between low and high is derived from the sum of [Low – Medium] – [High – Medium].

Source: FTI-CL Energy modelling

The medium scenario meets the EU renewables objectives by 2030 and projects further renewable growth to reach 81% of generation in 2050

RES penetration:

- By 2030, in line with EU RES objectives, RES penetration gets above 56%.
- By 2050, increased cost competitiveness of Wind and Solar leads to reach 81% RES share in total generation (excluding storage), with 68% of variable RES (wind and solar) and 14% of controllable RES (biomass, other RES and hydro)

Thermal generation:

- Thermal generation decreases from 36% in 2020 to 3% by 2050. By 2050, thermal generation mainly comes from the "Other" category including small distributed thermal non-renewable generation.

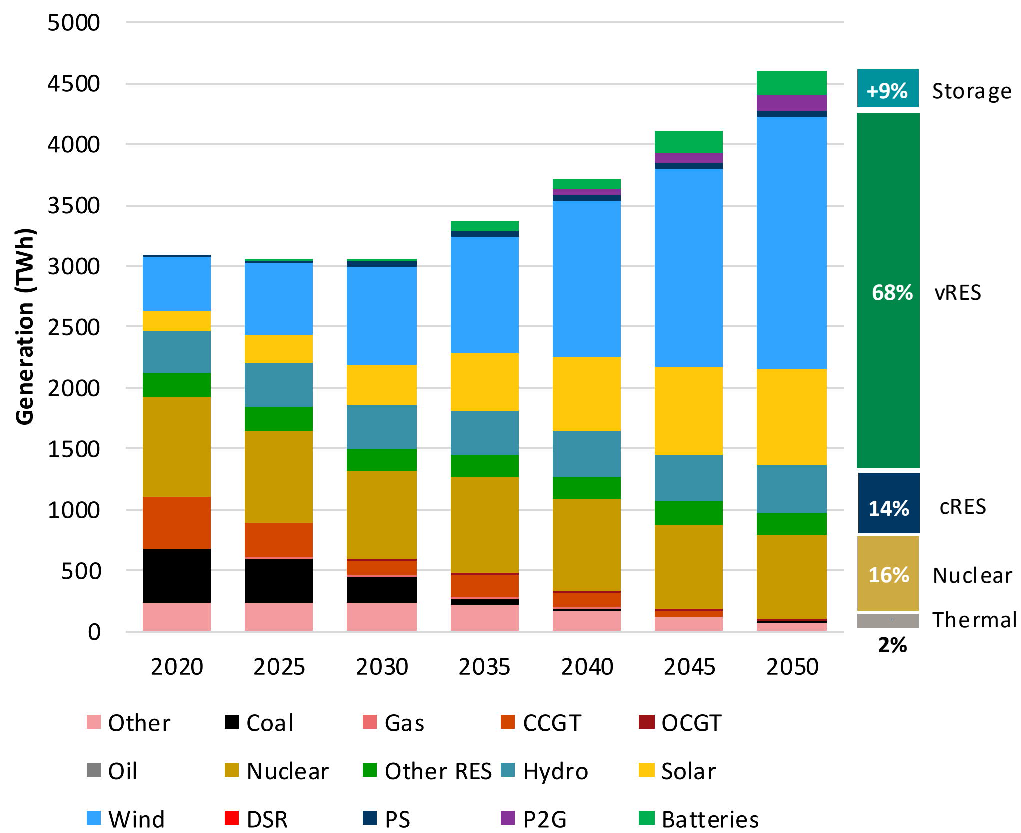
Storage :

- Non-consumed RES production increases to 580TWh in 2050, of which 370TWh are reinjected in the system through storage (Battery and P2G) generation.

Nuclear :

- Nuclear generation decreases to 680TWh in 2050 or 16% of total generation.

Medium scenario generation outlook



Source: FTI-CL Energy modelling

Note: Non-consumed RES production not reinjected in the system corresponds to storage net consumption (due to efficiency loss)

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"; vRES includes wind and solar; cRES includes Hydro and other RES

While both scenarios meet the long term objective, the low scenarios relies more heavily on variable RES and back-up sources

RES penetration:

- In the low scenario, RES reach 92% of total 2050 generation, with 79% penetration of variable RES.
- In the high scenario, RES reach 74% of total 2050 generation, with 60% penetration of variable RES.

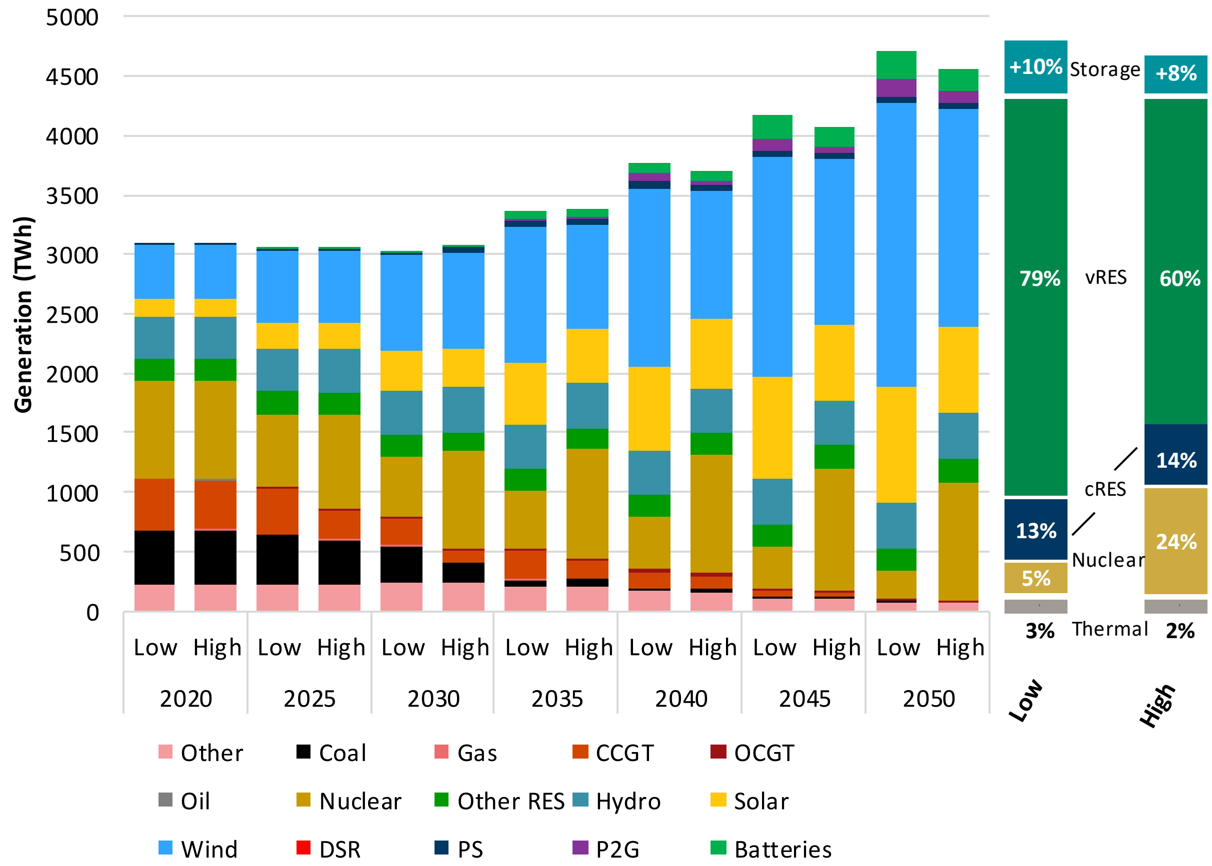
Storage :

- In the low scenario, RES would produce 690TWh of non consumed energy, 440 of which being stored and redistributed through P2G or batteries.
- In the High scenario, RES would produce 525TWh of non consumed energy, 345 of which being stored and redistributed through P2G or batteries.

A reduction of 114GW of nuclear would require to bringing the variable RES share to around 80%, beyond current EU-wide acceptable variable renewable penetration level.

A high nuclear scenario would manage to contain the variable RES share to around 60%, strengthening system stability in the long term.

Low and High scenario generation outlook



Source: FTI-CL Energy modelling

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”; vRES includes wind and solar; cRES includes Hydro and other RES

Note: Non-consumed RES production not reinjected in the system corresponds to storage net consumption (due to efficiency loss)

In the low scenario, anticipated nuclear capacity closure increase thermal generation and curtailed energy induced by variable RES

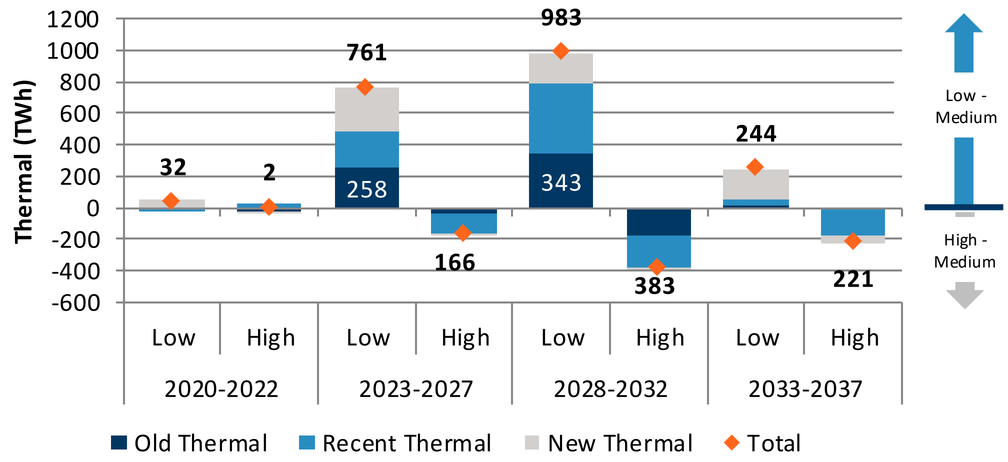
Comparison of the Low and High scenario generation outlook :

- Anticipated closure of nuclear capacity would induce about **2790TWh of additional thermal generation** in the short term to medium term representing a **+20% increase** or the equivalent of 4 years of projected thermal generation.
  - Old carbon intensive thermal plants take up 30% of this additional generation (860TWh)
  - Recent thermal plants take up 40% of the additional generation (1165TWh).
- In the longer term, anticipated nuclear closure and limited new nuclear investments would induce about **66TWh of additional curtailed energy in 2050**, or 1% of the total RES generation. It represents a **+160% increase** between both scenarios.

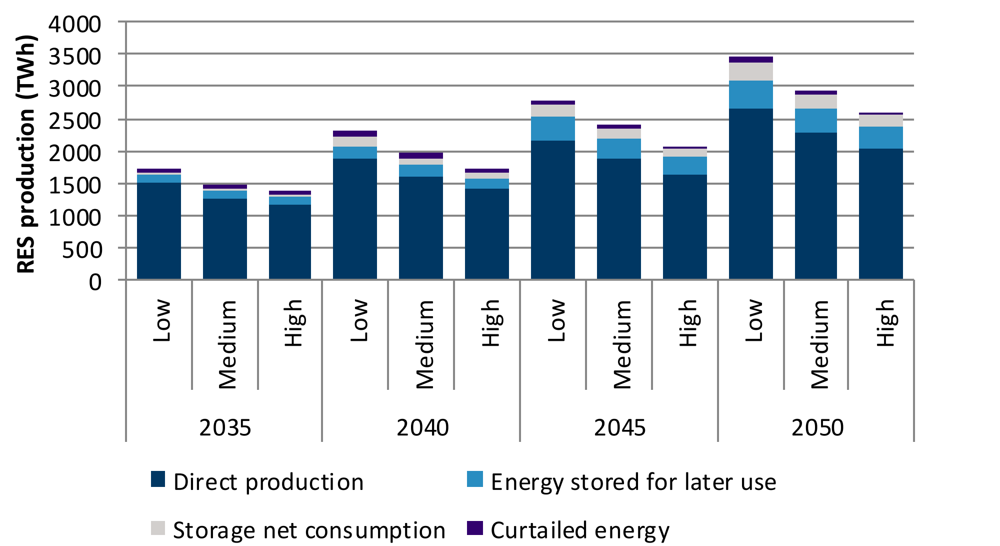
A low nuclear generation would heavily rely on thermal generation in the short to medium term before transitioning towards an less efficient generation mix featuring much higher level of variable RES curtailed energy.

Note: comparison between low and high is derived from the sum of (Low - Medium) – (High - Medium).

Additional generation compared to medium scenario



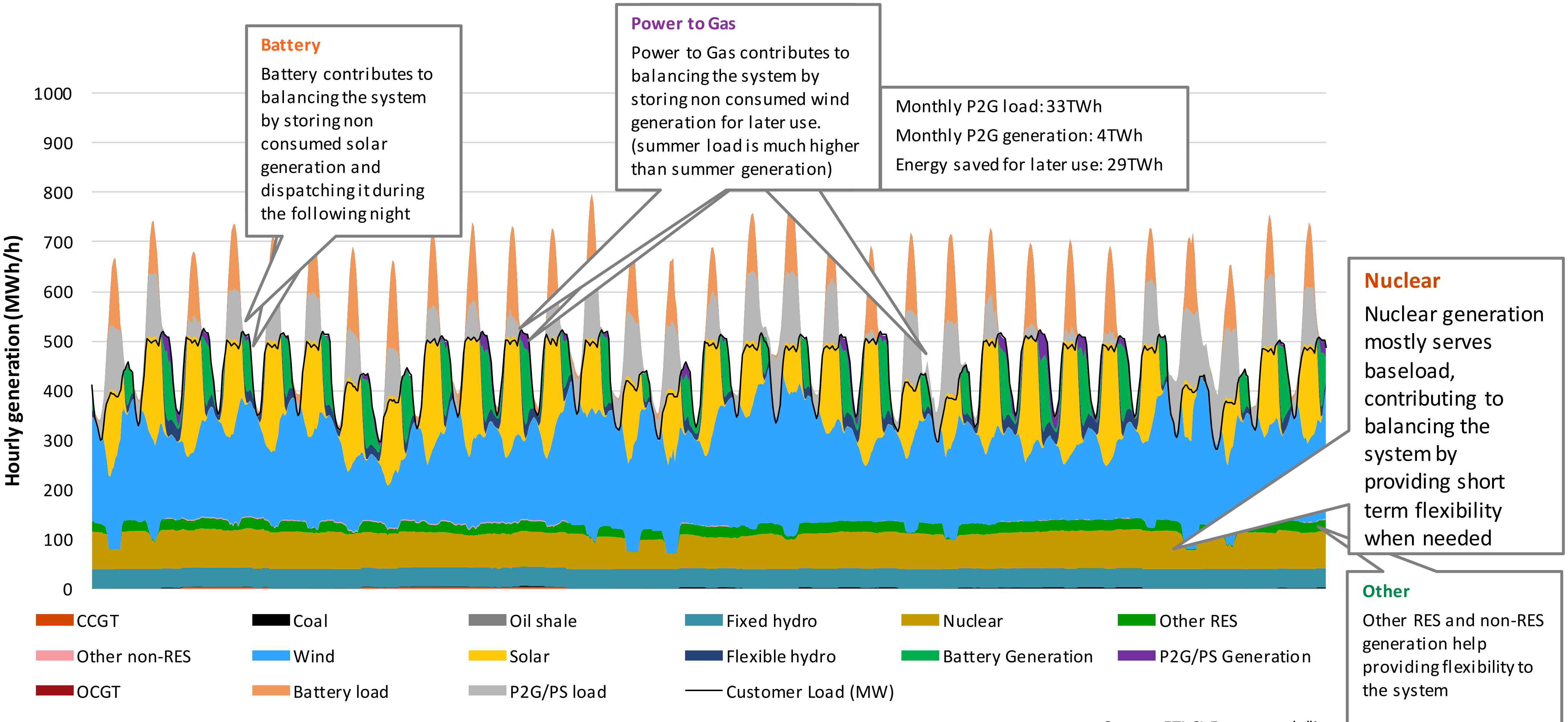
RES (wind, solar) production comparison



Source: FTI-CL Energy modelling

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

Hourly generation mix during a summer month – July 2050

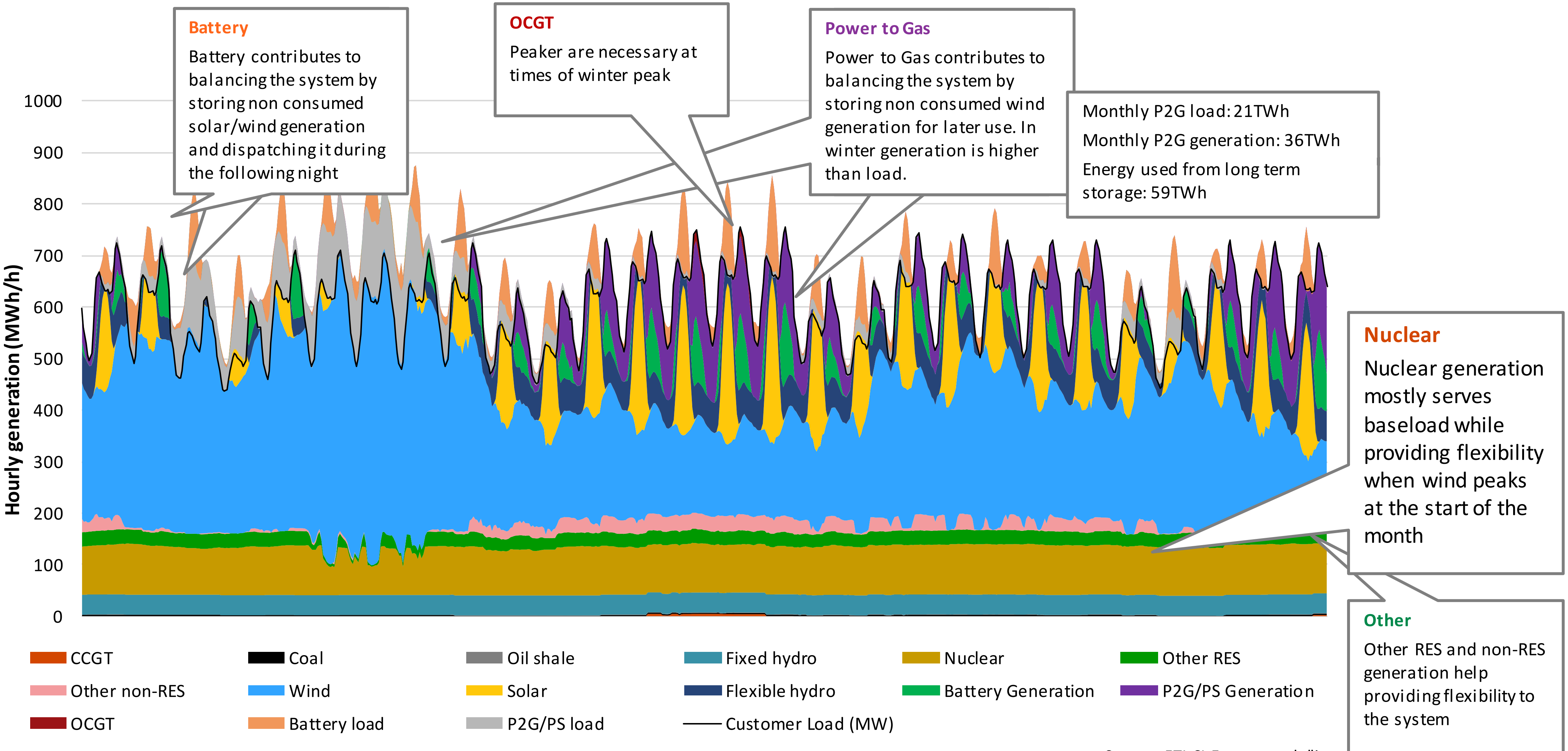


Source: FTI-CL Energy modelling

Note: PS stands for Pumped Storage

In the 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 – February 2050



Source: FTI-CL Energy modelling

Optimising the use of short term and long term storage will be critical to maintain an efficient and economic operation of nuclear plants

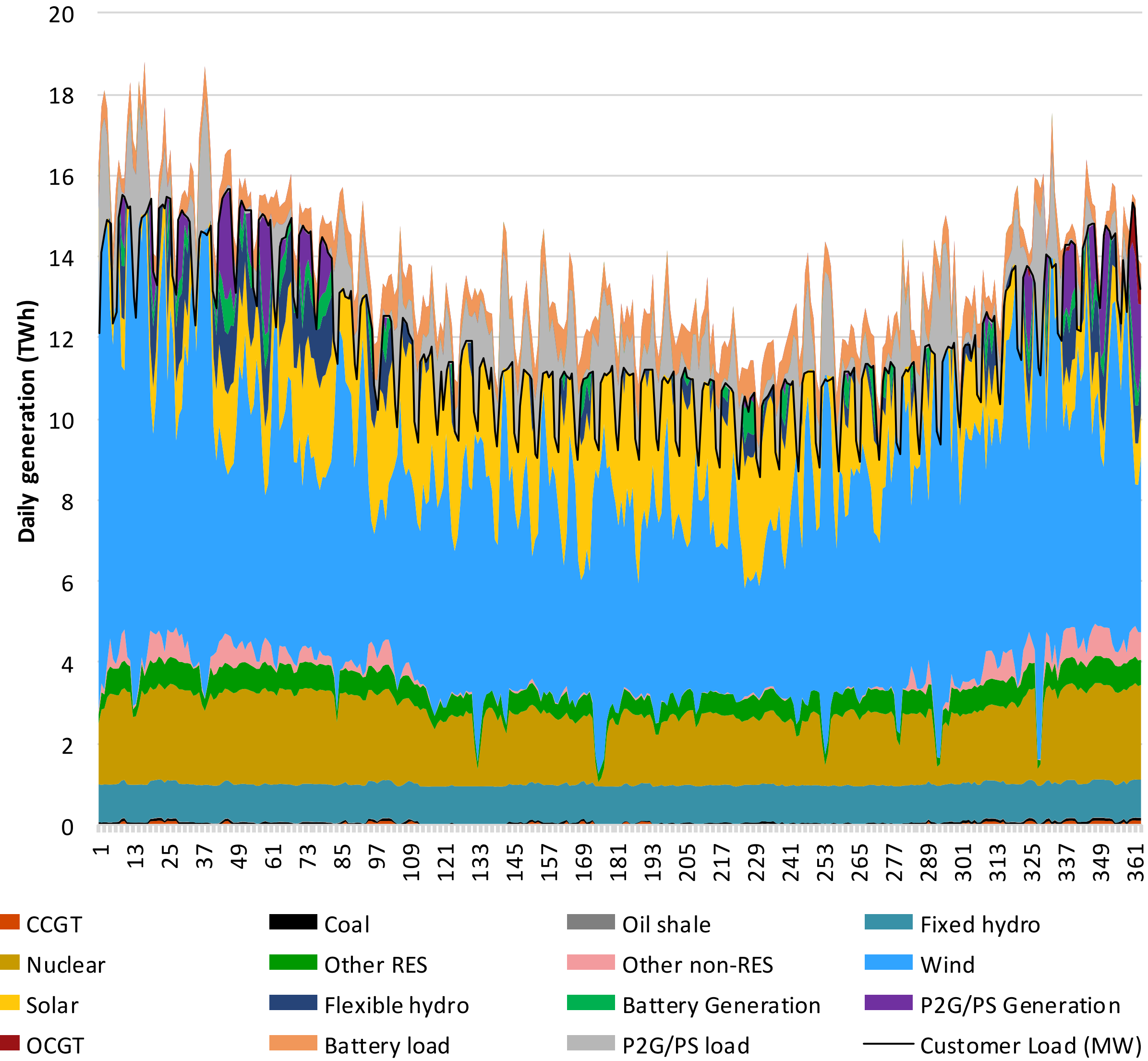
Nuclear contributes to providing flexibility and baseload power to the system by cycling at different times:

- **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 10% 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 20% of the customer load.

Daily generation mix - 2050



Source: FTI-CL Energy modelling

The nuclear average capacity factor remains above the 70% threshold in all three scenarios

In all three scenarios, the nuclear average capacity factor remains above the 70% threshold over 2020-2050.

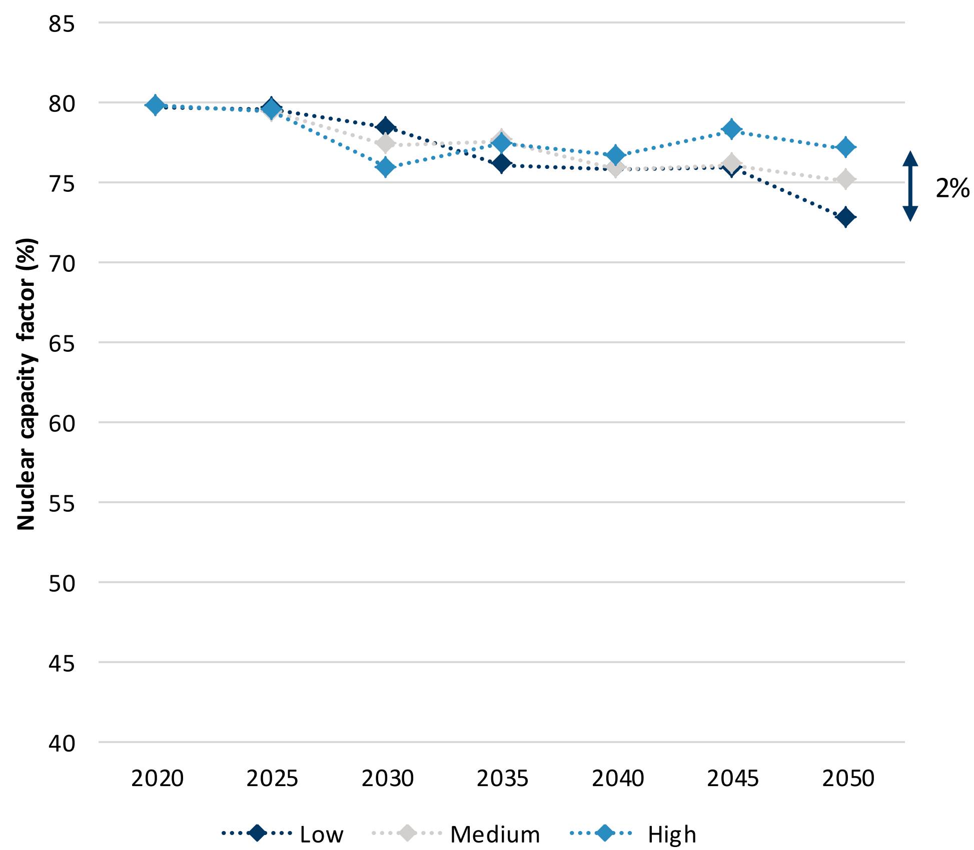
The average nuclear capacity factor decreases slightly in each scenario with the growth of RES - particularly after 2035:

- In the Low nuclear scenario, faster growth of RES would further decrease nuclear average capacity factor by 2% in 2050.
- 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: FTI-CL Energy modelling

Increased nuclear generation in the high scenario would reduce consumption of fossil fuels by up to 6500 TWh between 2020 and 2050

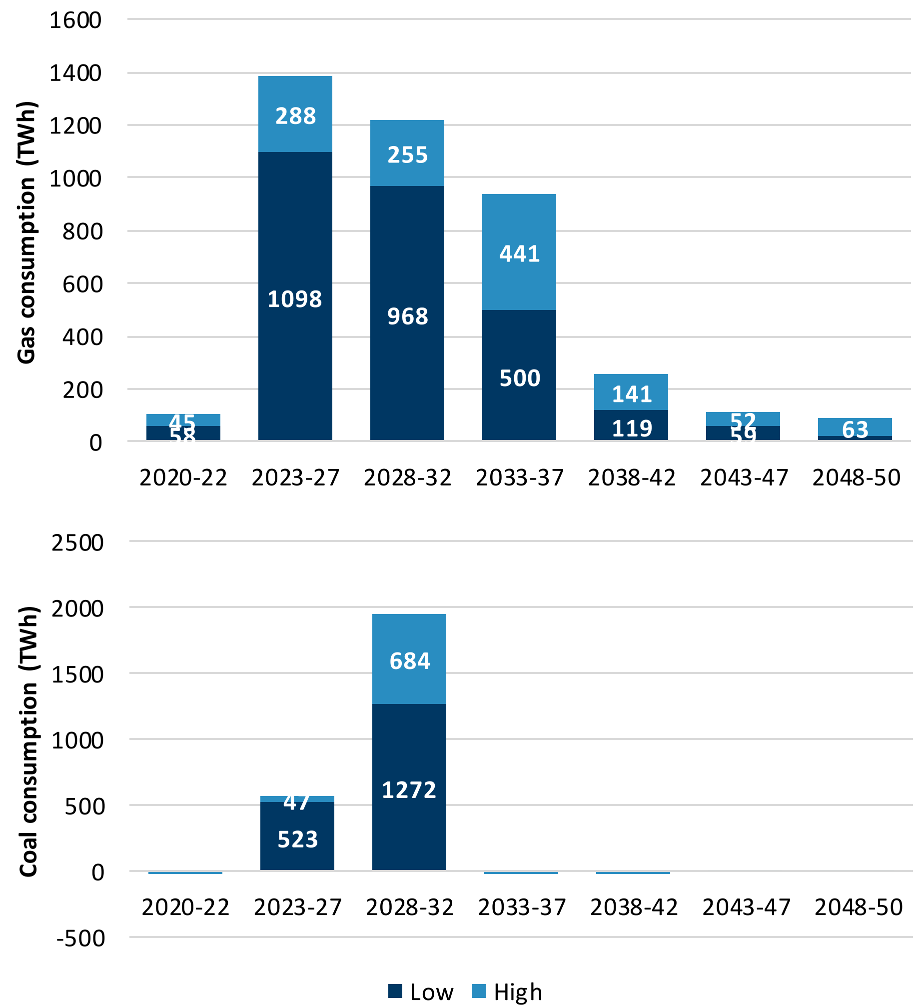
Increased nuclear generation in the high scenario compared to the low scenario would avoid 4100TWh of gas consumption between 2020 and 2050:

- Equivalent to 4.8 years of 2020 gas consumption from the power sector, or **36% of the 2020-2050 overall gas consumption from the power sector**.

Increased nuclear generation in the high scenario compared to the low scenario would avoid 2400TWh of coal consumption between 2020 and 2050 :

- Equivalent to more than a year of 2020 coal consumption from the power sector, or **18% of the 2020-2050 overall power sector coal consumption.**

Fossil fuel consumption difference from the power sector



Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Source: FTI-CL Energy modelling

In the low scenario, nuclear closure and limited nuclear investments would induce c2270 MtCO2 of additional emissions in the short term

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

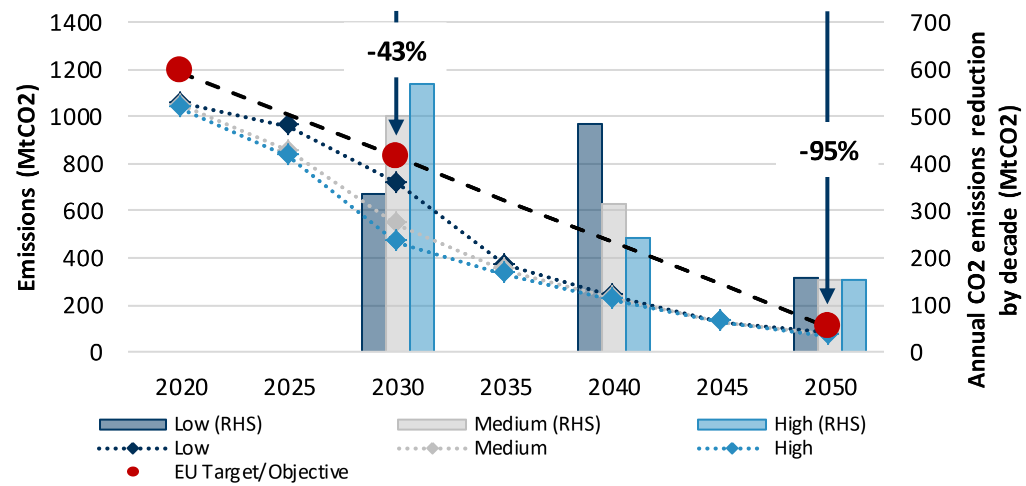
Anticipated nuclear closure and limited new nuclear investments in the low scenario would materially increase total emissions over 2020-2050:

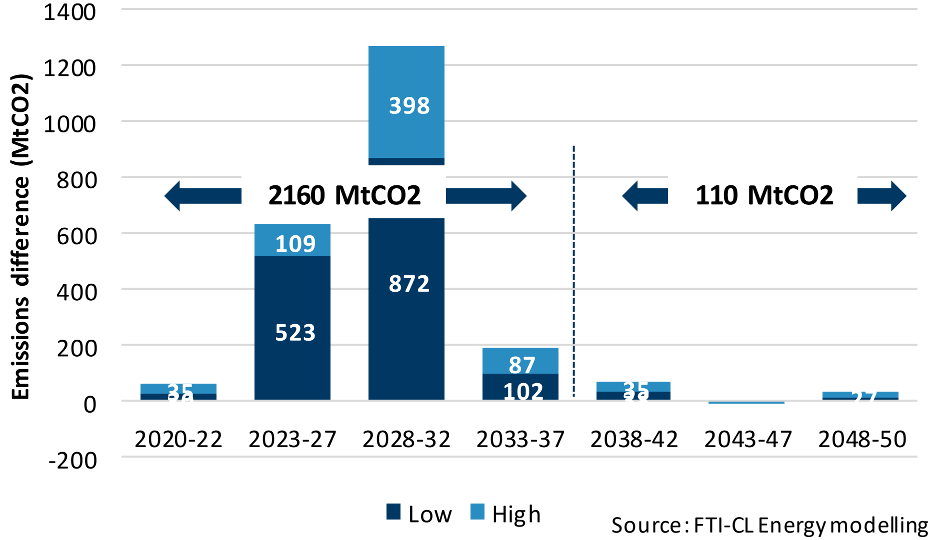
- An early closure of nuclear plants would require new thermal plants in order to ensure security of supply, , as well as additional thermal generation from existing plants which would generate c**2270Mt** of additional CO2 emissions or **17% of total CO2 emissions from the power sector** over 2020-2050.

Furthermore, most of the CO2 savings would occur in the short to medium term (by 2035), facilitating the EU transition before further roll-out of variable renewable and storage.

Note: While all three 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.

CO2 emissions outlook from the power sector





Source: FTI-CL Energy modelling

Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

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.

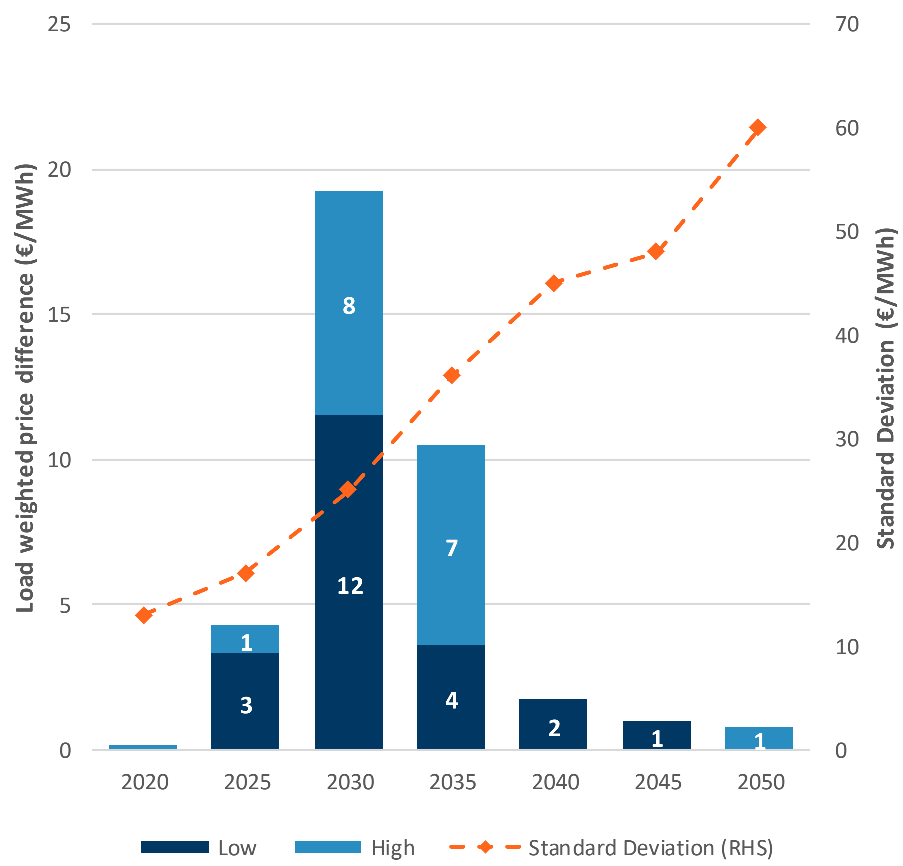
- Across Europe, the power price impact of lower nuclear generation in the low scenario compared to the high scenario **averages at around 5€/MWh**, reaching 20€/MWh in 2030s when anticipated closures significantly increase fossil fuel consumption:
  - Anticipated nuclear closure would increase the frequency 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 in all three scenario, the volatility of power prices significantly increases, driven by the increasing variable RES penetration.

Note: Power prices converge in all three scenarios in the long term as the generation is mix is optimised through the addition of variable RES and storage.

Power price difference outlook across scenarios (real 2017)



Sourc: FTI-CL Energy modelling

Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Source: FTI-CL Energy modelling

In the low scenario, customer cost would increase by about €350 billion over 2020-2050 compared to the high scenario

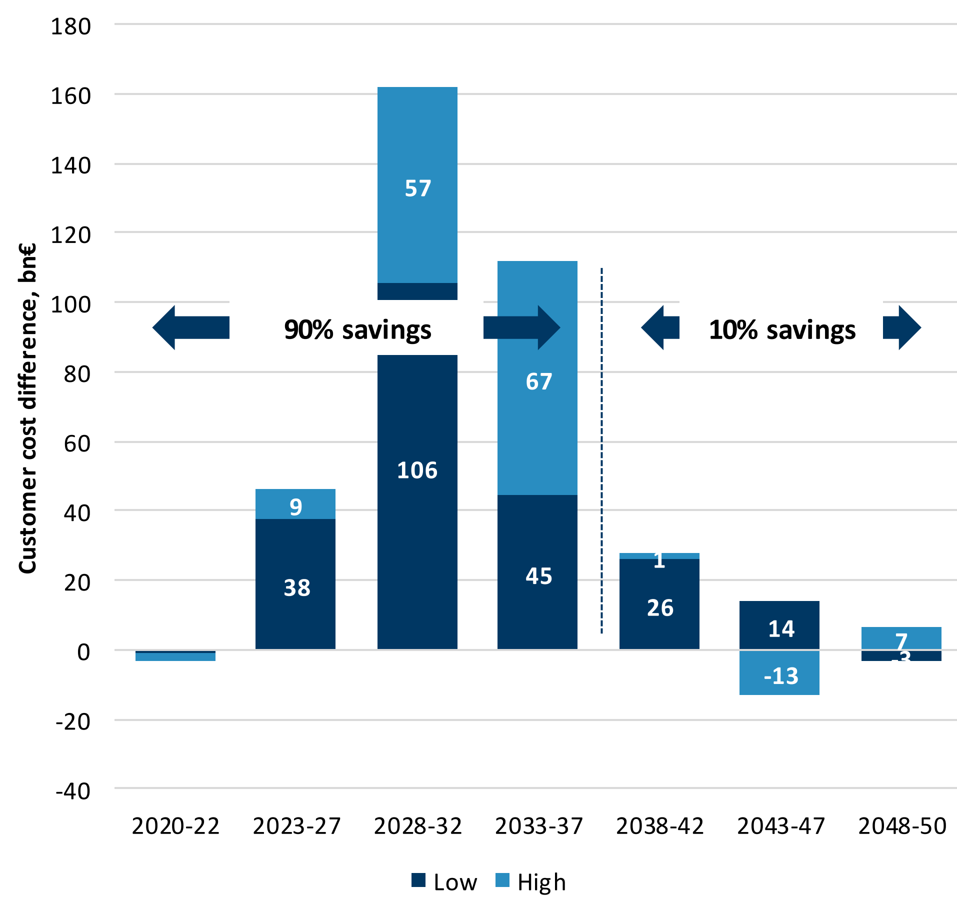
Anticipated nuclear closure in the low scenario compared to the high scenario would impact customer cost through:

- **Energy cost increase:**
  - **+€575 billion** additional cost as cheap nuclear baseload is replaced by more expensive gas and coal generation in the short to medium term;
- **Partly offset by reduced generation capacity cost:**
  - **-€15 billion** from reduced investment in low carbon baseload generation in the short to medium term;
- **And lower low carbon subsidy cost:**
  - **-€210 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 €350 billion over 2020-2050, c5% of total customer cost over 2020-2050.

Furthermore, 90% of these savings on customer benefit would occur in the short to medium term before 2035, further strengthening the contribution of nuclear generation in the transition to decarbonisation

Customer cost difference outlook (real 2017)



Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Source: FTI-CL Energy modelling

The low scenario would reduce the residual value of investments by €960 billion in 2050 compared to the high scenario

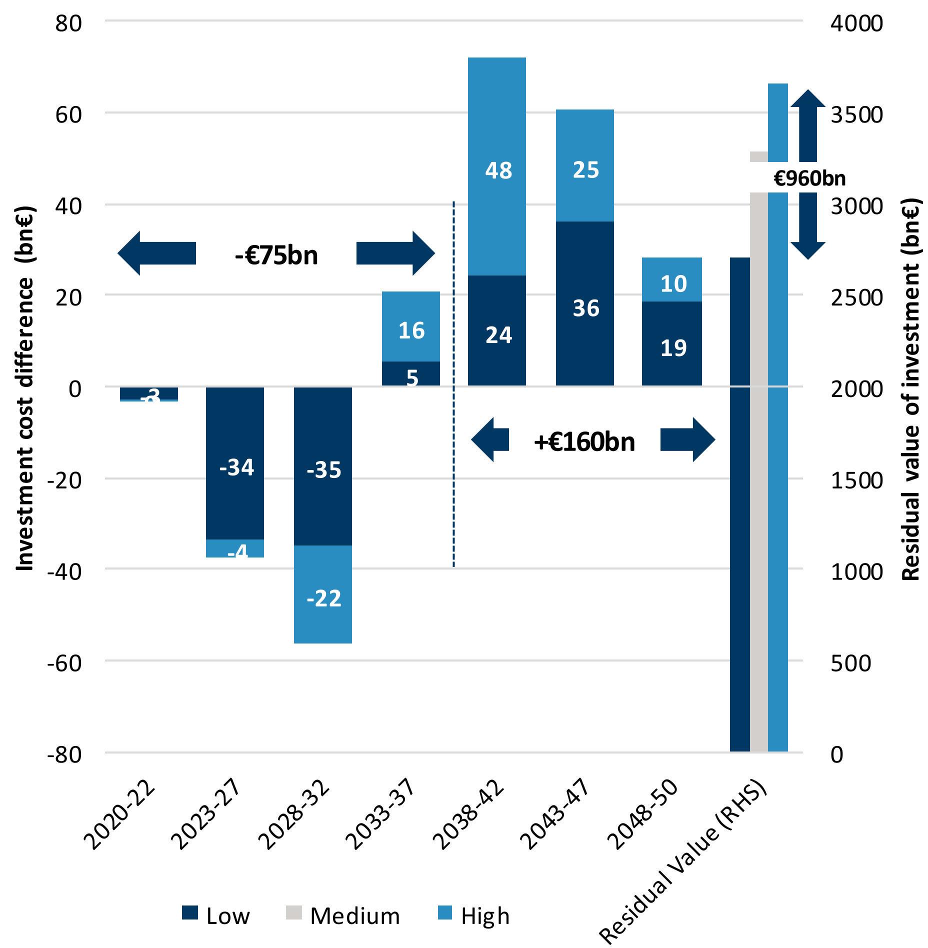
The low scenario would increase investment cost by €85 billion over the high scenario (2.6% increase):

- Anticipated nuclear closure would save €75 billion in the short to medium term before increasing investment cost by €160 billion in the long term.
- It represents a 2.6% increase of the investment cost compared to the medium scenario.

The low scenario would decrease the residual value of investment by €960 billion in 2050 compared to the medium scenario (29% 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.

Investment cost difference (undiscounted) and residual value over 2020-2050



Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Source: FTI-CL Energy modelling

In the High scenario featuring new nuclear, investment and customer costs results are robust to nuclear CAPEX assumption reduction

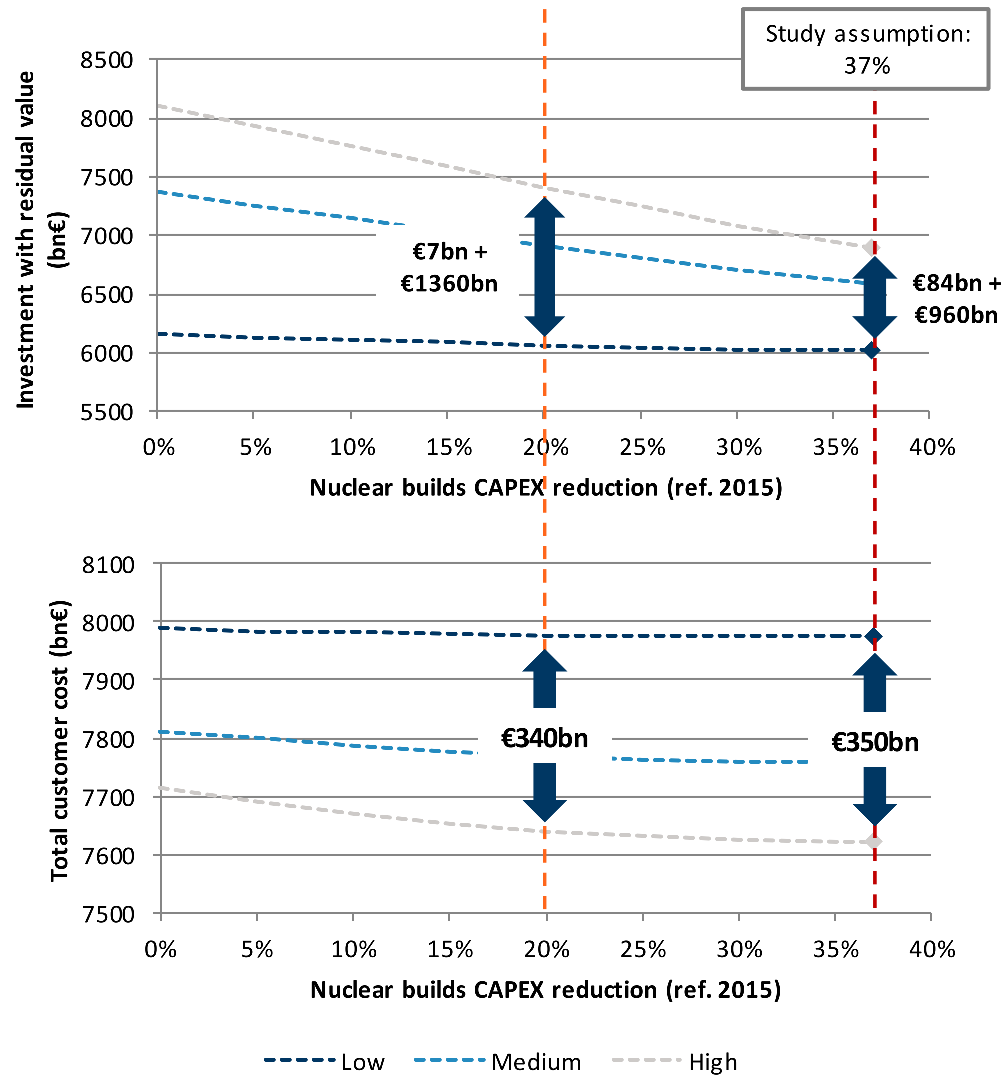
In the High scenario, costs are more sensitive to the nuclear CAPEX reduction assumption but results prove to be robust to nuclear CAPEX reduction assumption.

- At 20% CAPEX reduction, investment costs savings during 2020-2050 would decrease from €84bn to €7bn, while residual value benefits would increase from €960bn to €1360bn.
- At 20% CAPEX reduction, total customer costs benefits would remain at a similar level, reducing from €350bn to €340bn.

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 to nuclear CAPEX of investment and costs



Source: FTI-CL Energy modelling

B Estimates of indirect costs and externalities

Methodology for the estimates of indirect costs 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 three 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 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 of labour intensity by generation 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

Direct jobs generated by generation technology

- The technology creating the greatest amount of direct jobs per MW installed is solar photovoltaic with 1.06 Jobs/MW.
- **Nuclear technology is the second most direct job intensive technology with 0.5 Jobs/MW**. It is also the most job intensive technology in terms of direct employment per site.

Technology	Jobs/MW	Average Size (MW)	Direct Local Jobs
Nuclear	0.50	1,000	504
Coal	0.19	1,000	187
Hydro > 500 MW	0.11	1,375	156
Hydro Pumped Storage	0.10	890	85
Hydro > 20 MW	0.19	450	86
Concentrating Solar Pwr	0.47	100	47
Gas Combined Cycle	0.05	630	34
Solar Photovoltaic	1.06	10	11
Micro Hydro < 20 MW	0.45	10	5
Wind	0.05	75	4

Source: OECD/IAEA 2015

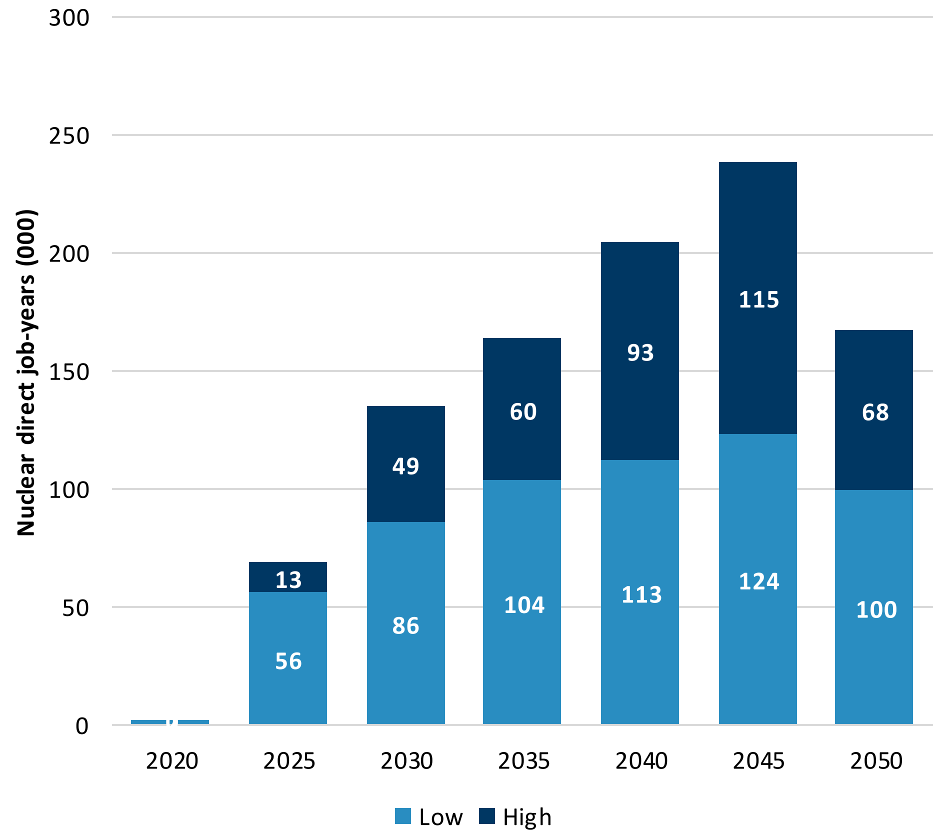
A higher share of nuclear power would create about 1 million high skilled direct job-years in the nuclear generation sector over 2020-2050

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 three 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 high skilled jobs:

- An extension of nuclear plants followed by new investments across Europe would create 980 thousands high skilled job-years in the nuclear generation sector over 2020-2050, or +87% compared to the Low scenario.

Direct job impact in the nuclear generation sector



Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Source: FTI-CL Energy modelling

Estimates 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 grid 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 increase the Transmission and Distribution grid costs by about €160 billion in 2050

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.

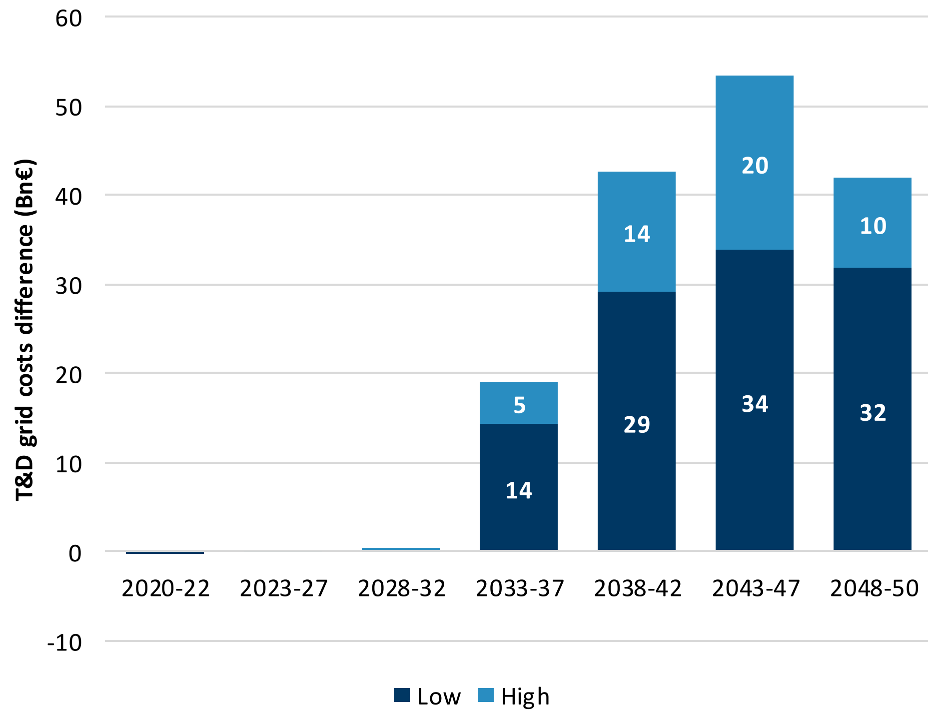
The low scenario with a higher share of RES would increase T&D grid costs compared to the high scenario:

- 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 **€160 billion** of additional T&D grid costs or **31% of the total T&D grid cost** cumulatively over the 2020-2050 horizon, of which €70 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.

Adding to customer cost benefits, it would bring total benefits to €440 billion over 2020-2050.

Undiscounted T&D grid costs difference



Source: FTI-CL Energy modelling

Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Note (1): T&D cost shown on the chart above are the additional T&D cost between 2020 and 2050.

Note (2): Offshore connection costs for Offshore Wind are accounted in the total investment cost (slide 43) as per EC convention.

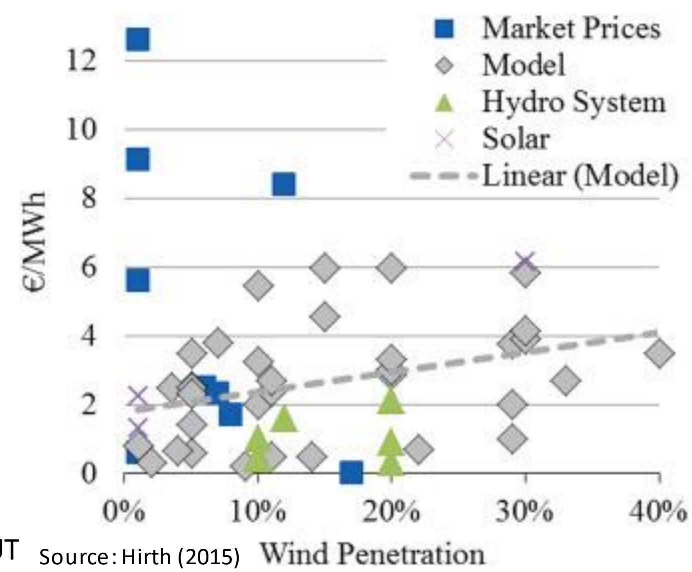
Estimates of balancing costs

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 increase total balancing costs by about €13 billion

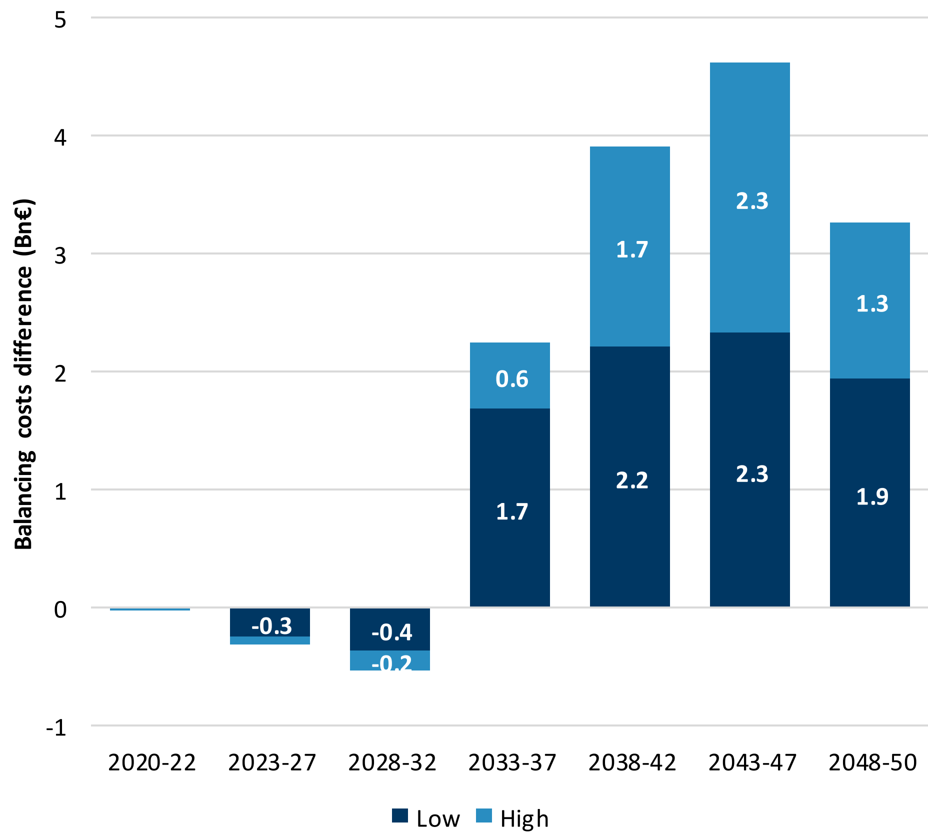
Whilst a thorough modelling of the effect on balancing costs of different scenarios is beyond the scope of this study, we provide a rough estimate based on the assumptions derived from our literature review.

In the low scenario, faster growth of RES and anticipated nuclear closure would increase balancing costs by €13 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 **€13 billion** of additional balancing costs or **15% 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 €455 billion over 2020-2050.

Undiscounted balancing costs difference



Source: FTI-CL Energy modelling

Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Estimates of land use by generation technology

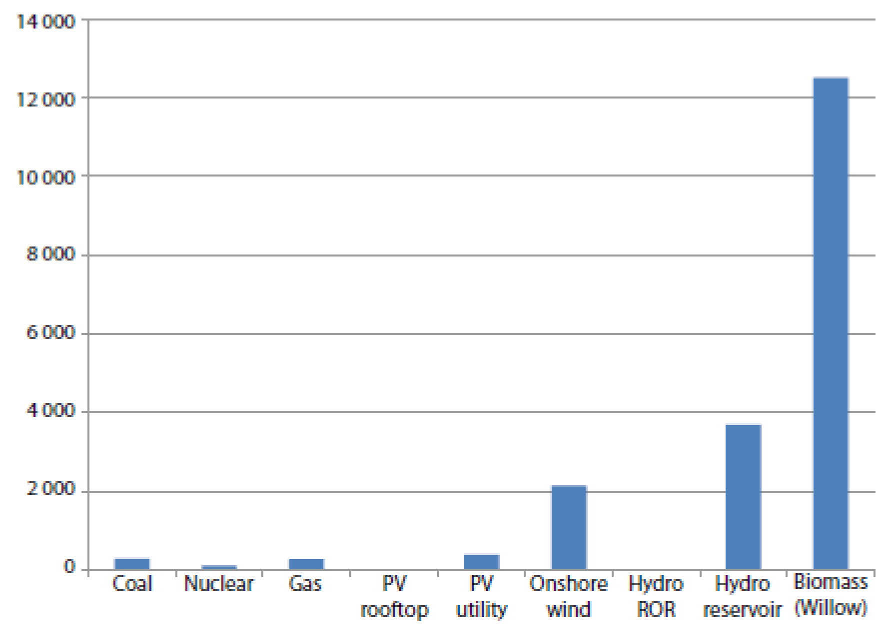
Literature review

- 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 requirements 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, m²/GWh)



Source: Based on Fthenakis and Kim, 2009.

In the High scenario, nuclear generation could reduce additional land use by 15790 km2 by 2050 compared to the Low scenario

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.

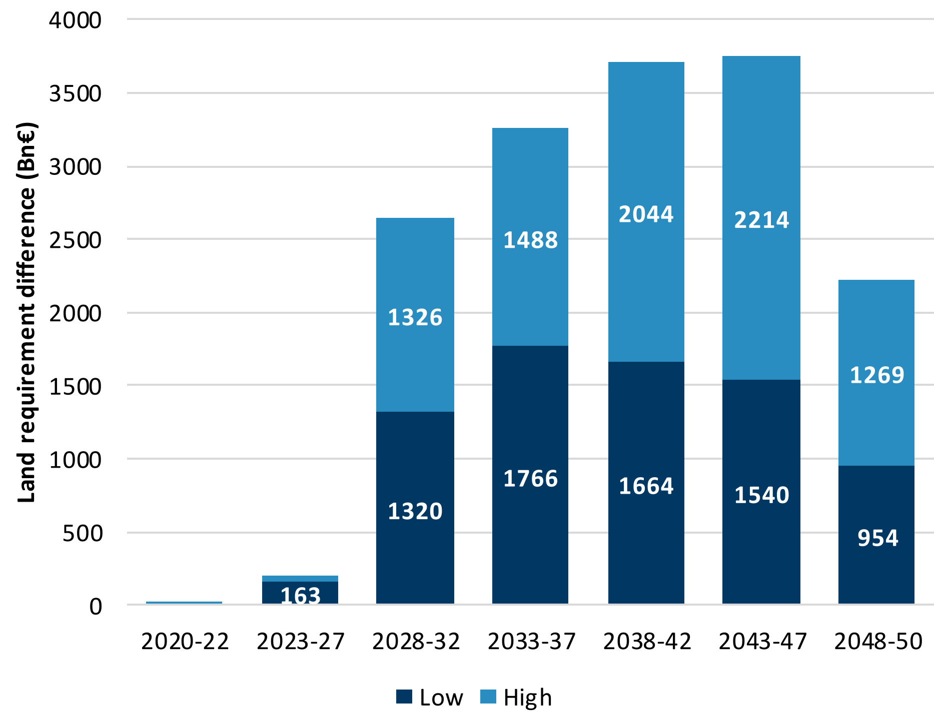
In the low scenario, nuclear closure and faster growth of RES would increase land use:

- An early closure of nuclear plants would require new solar and wind capacities in order to meet environmental objectives, which would generate **7410 km2** of additional land requirement or **5% of total land use** over 2020-2050.
- This would be a bit less than three times Luxemburg area.

A high nuclear scenario featuring new plants would further decrease the land requirement compared to the medium scenario:

- The high scenario saves an additional **8380 km2** of land requirement compared to the medium scenario, representing **5% of total land use** over 2020-2050, bringing the total land requirement savings to half of the area of Belgium.

Additional land requirement difference



Source: FTI-CL Energy modelling

Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Note: this does not account for the maritime area of Offshore wind farms

Estimates 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.

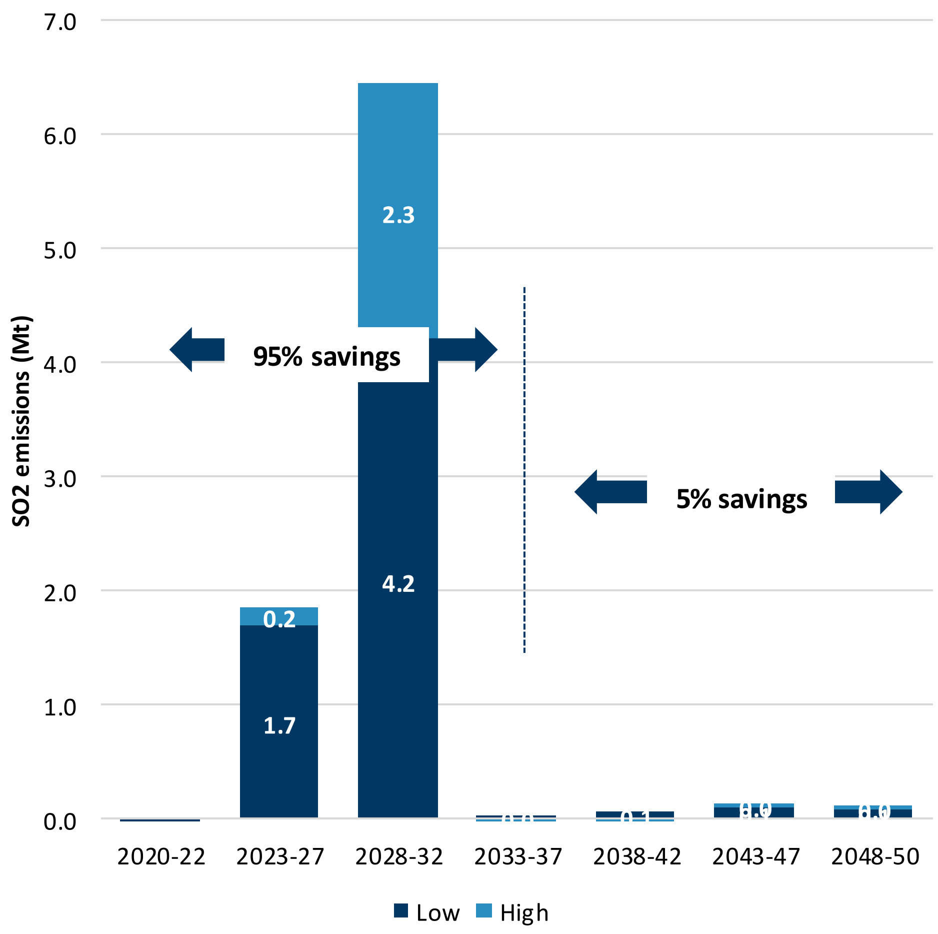
In the low scenario, SO2 emissions would increase by 8Mt over the 2020-2050 horizon compared to the high scenario

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 three 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 **8Mt** of additional SO2 emissions or **15% of total SO2 emissions** over 2020-2050.

Cumulative SO2 emission estimates across scenarios



Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Source: FTI-CL Energy modelling

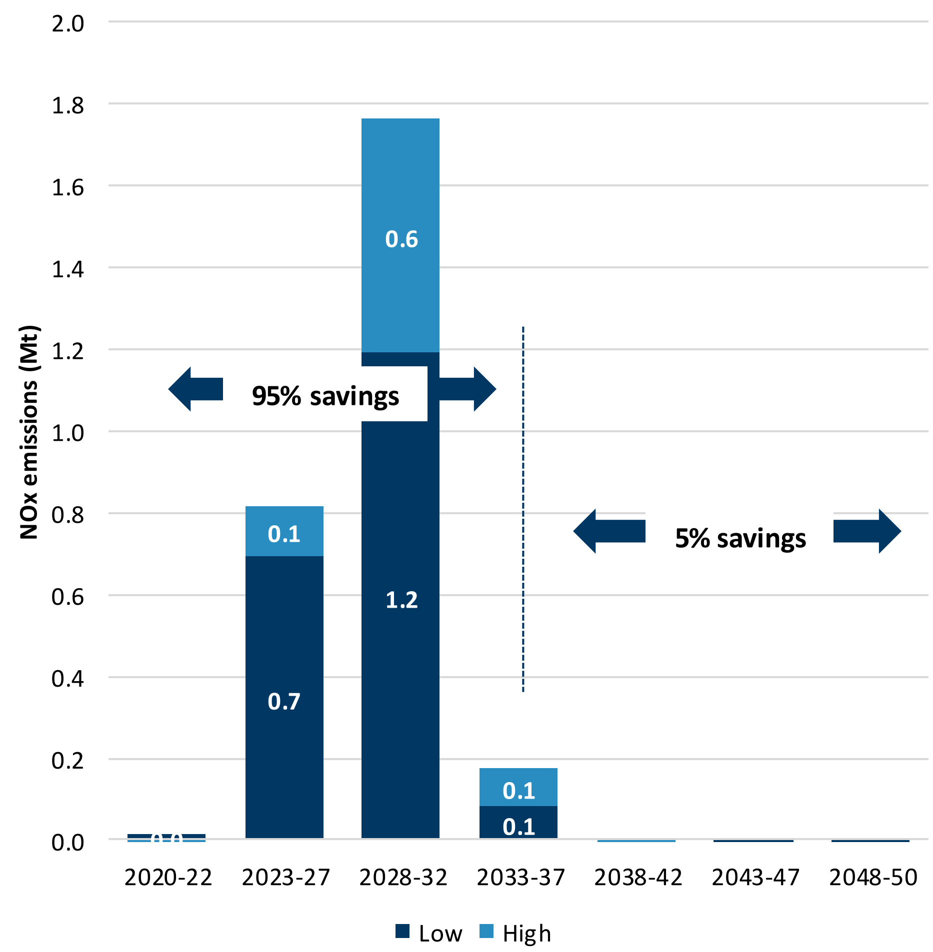
In the low scenario, NOx emissions would increase by 3Mt over 2020-2050 compared to the high scenario

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 **2Mt** of additional NOx emissions or **9% of total NOx emissions** over 2020-2050.

NOx emission estimates across scenarios



Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

Source: FTI-CL Energy modelling

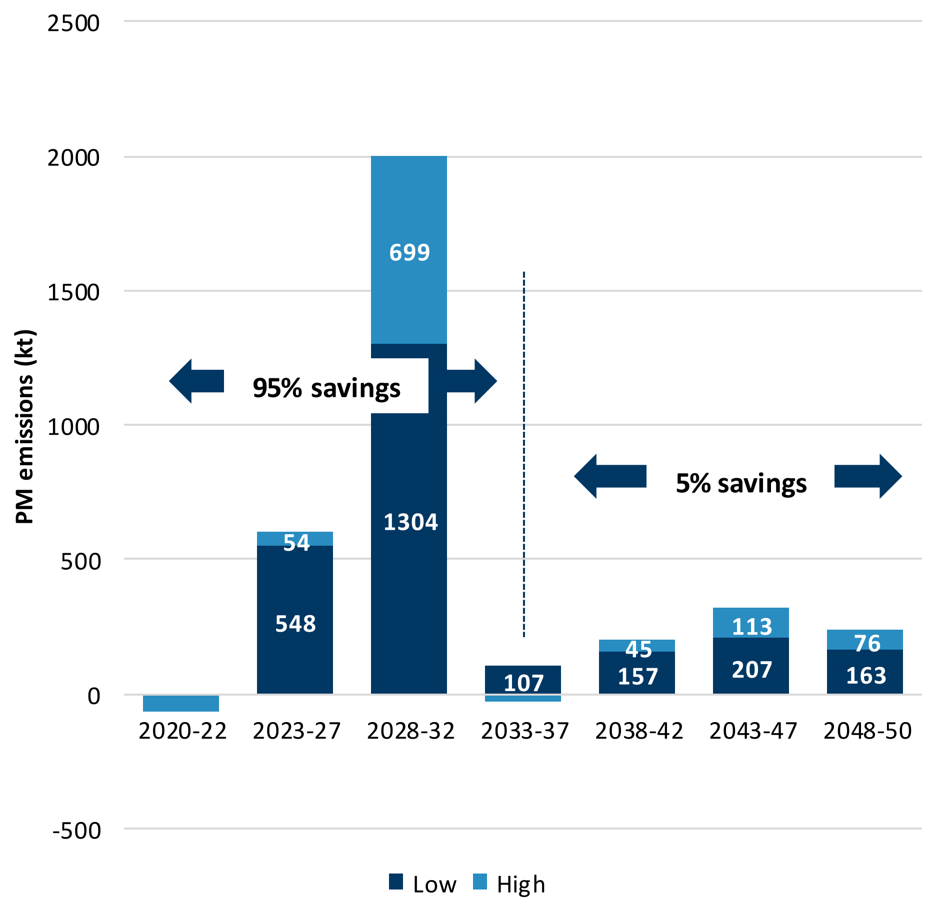
In the low scenario, particulates emissions would increase by 3400kt over 2020-2050 compared to the medium scenario

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 **3400kt** of additional PM emissions or **18% of total PM emissions** over 2020-2050.

PM emission estimates across scenarios



Note: Low compares Low – Medium scenario; High compares Medium – High scenario.

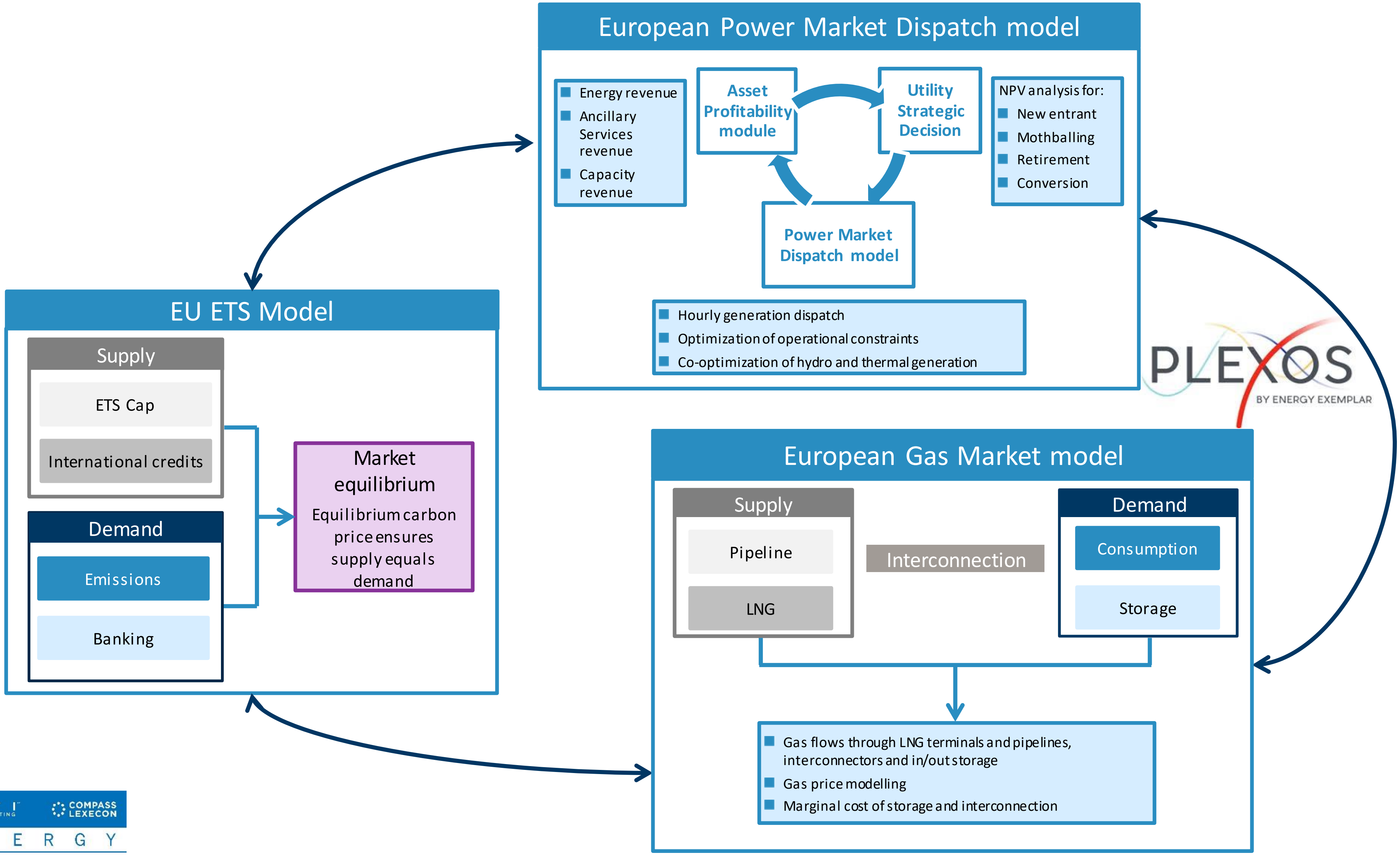
Source: FTI-CL Energy modelling

4

Appendices

Appendix 1: FTI-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

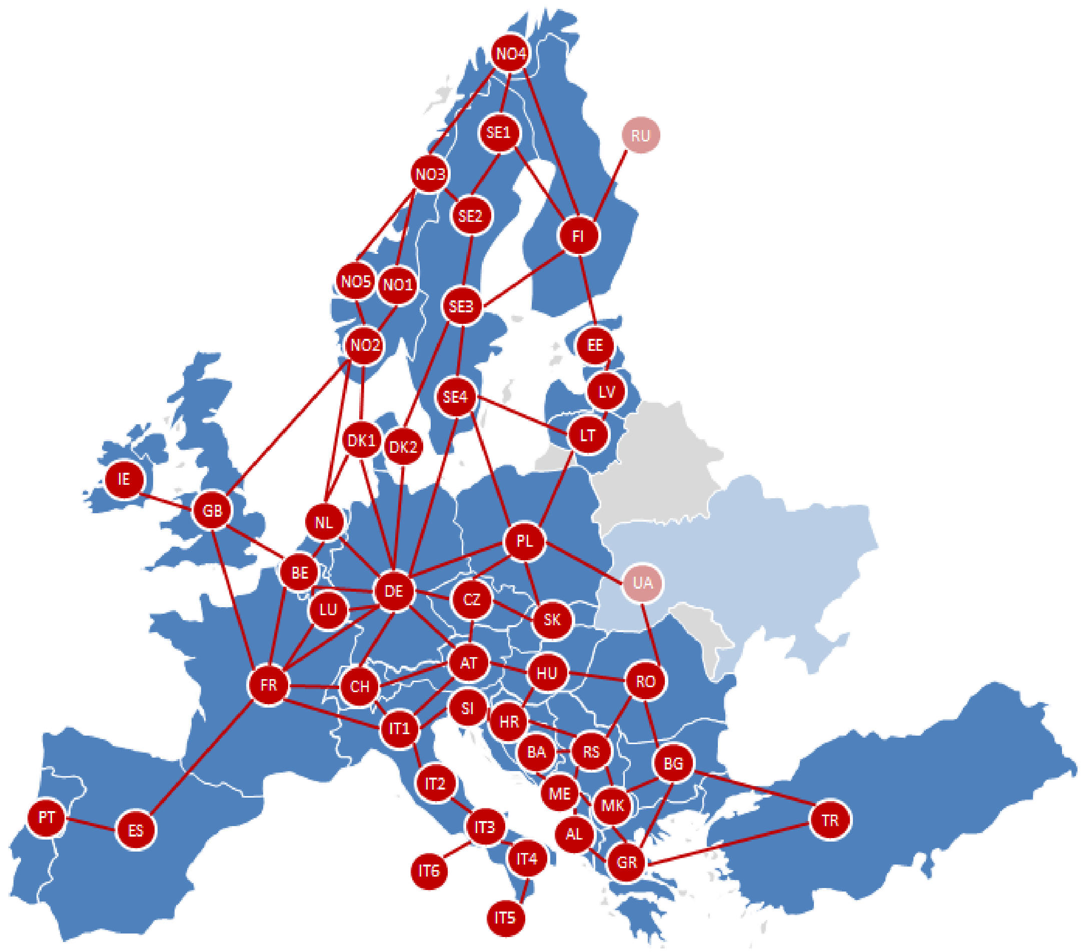
Overview of FTI-CL Energy's power market model

- 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



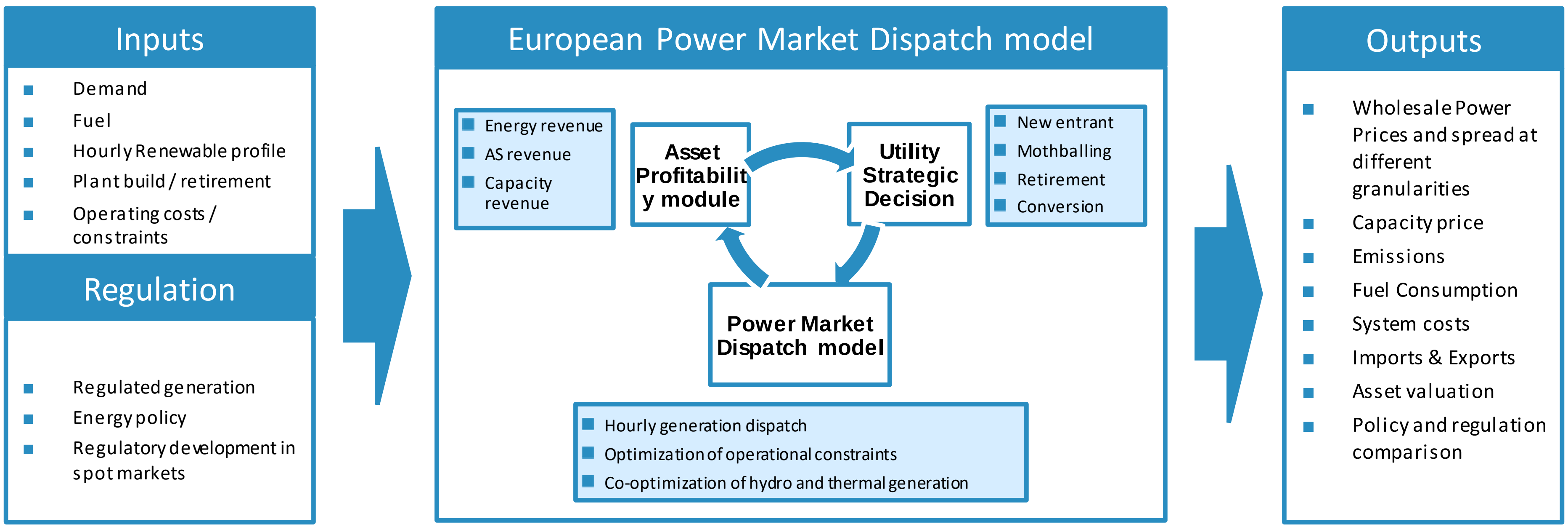
FTI-CL Energy’s power market model relies on a dispatch optimisation software with detailed representation of market fundamentals

Dispatch optimisation based on detailed representation of power market fundamentals

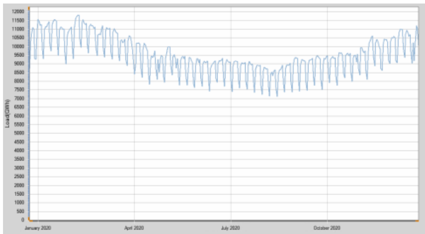
- At the heart of FTI-CL Energy’s market modelling capability lies a dispatch optimisation software, Plexos®, based on a detailed representation of market supply and demand fundamentals at an hourly granularity. Plexos® is globally used by regulators, TSOs, and power market participants.

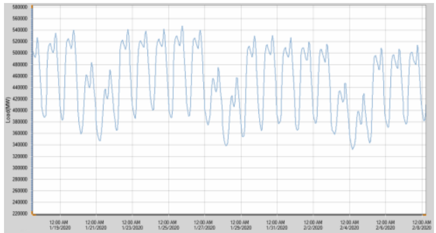
- FTI-CL Energy’s power market model is specifically designed to model renewable generation:
  - Wind: Hourly profiles are derived from our in-house methodology that converts consolidated wind speeds into power output.
  - Solar: Hourly profiles are derived from our in-house methodology that converts 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®.

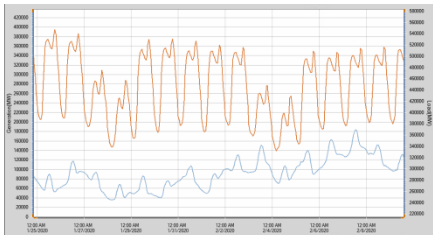
FTI-CL Energy’s modelling approach (input, modules and output)

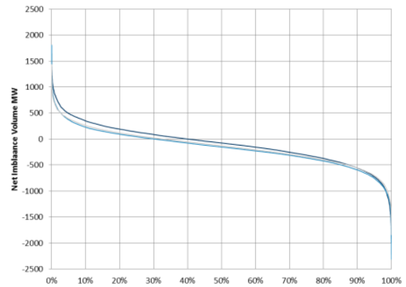


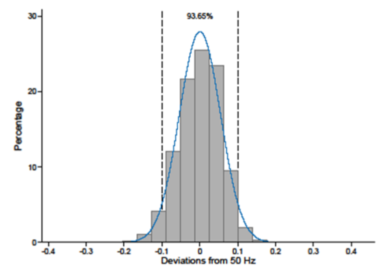
FTI-CL Energy's power market suite allows to capture the flexibility and market arbitrage values on short time frames

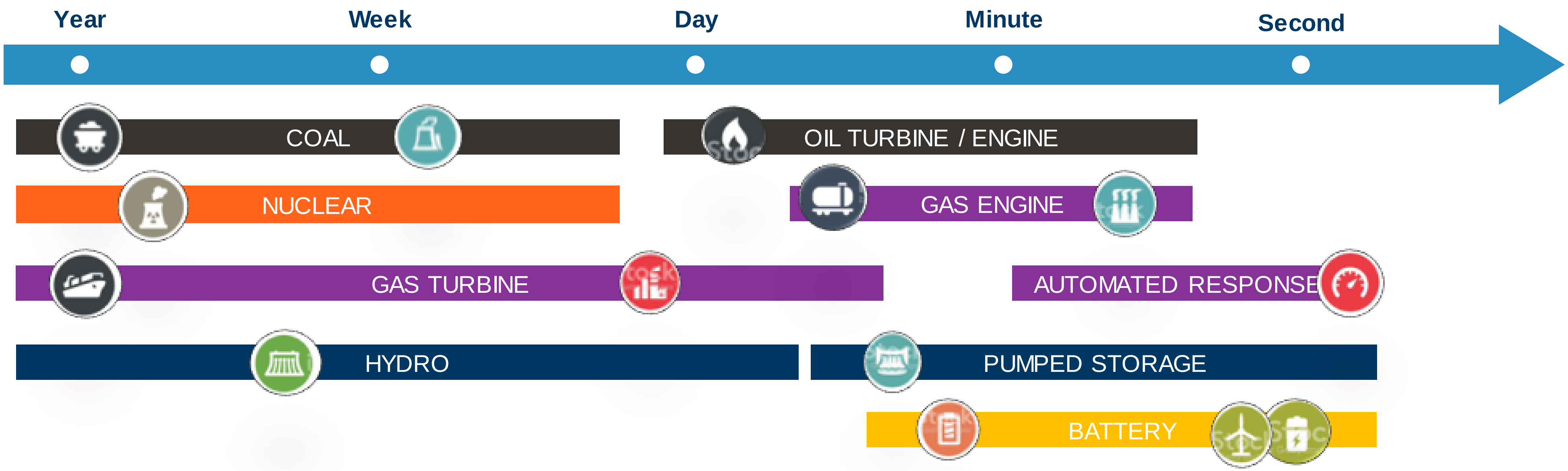












Appendix 2: Key modelling assumptions

The Electric Vehicle outlook shows a steep increase to 2050 in line with ENTSOE EUCO30 and EURELECTRIC's latest outlook

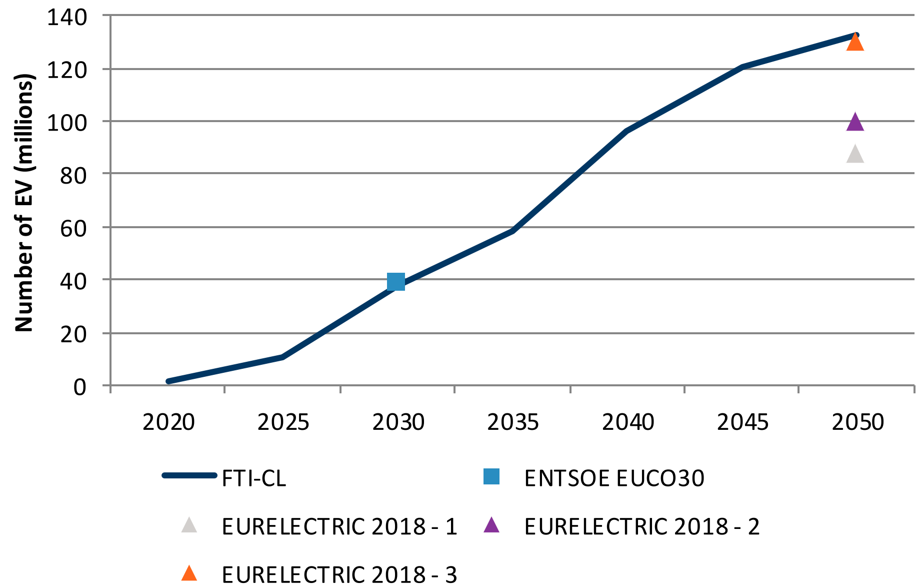
A strong EV deployment generating an important load

- The EV stock grows from 1.6 million in 2020 to **133 million in 2050**, representing a penetration of 250 EV/1000inh or 98% of the total vehicle fleet.
- Our outlook is comparable with the latest EURELECTRIC's high case scenario featuring 130 million EV by 2050.
- It corresponds to a **388 TWh** additional load based on consumption data from ENTSOE[1].
- All EV are assumed to have the same demand profile across EU-28. Their load is based on their daily load profile and a seasonality factor, provided by ENTSOE.

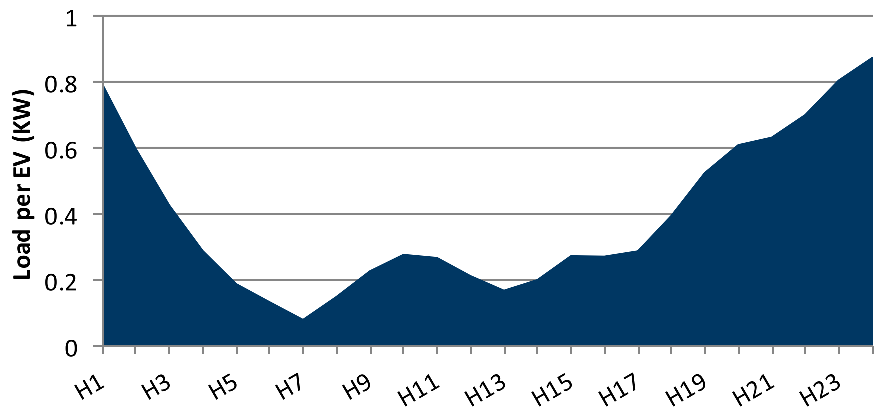
We project a high EV deployment throughout EU in line with most recent studies. To reflect future smart charging system, half of the EV stock is modelled as responsive to power price.

[1] Higher than the 256TWh projected by EURELECTRIC. We use a consumption per car value of 2.9 KWh provided by ENTSOE. It corresponds to the upper band of the values used in EURELECTRIC Decarbonization pathways.

Number of EV outlook and hourly load



EV hourly load



Sources: FTI-CL Energy analysis, Eurelectric, ENTSOE

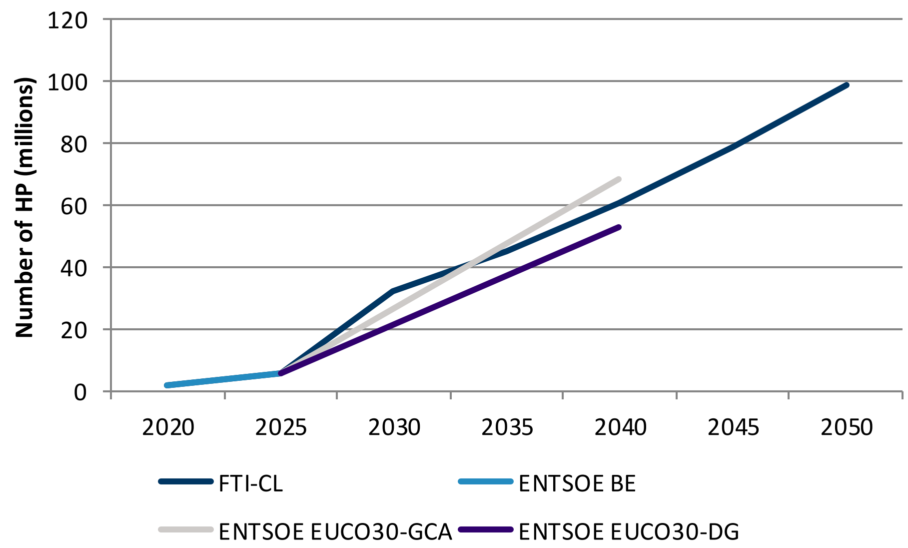
The Heat Pump outlook shows a steep increase to 2050 in line with ENTSOE EUCO30 outlook

Additional load from increasing number of HP

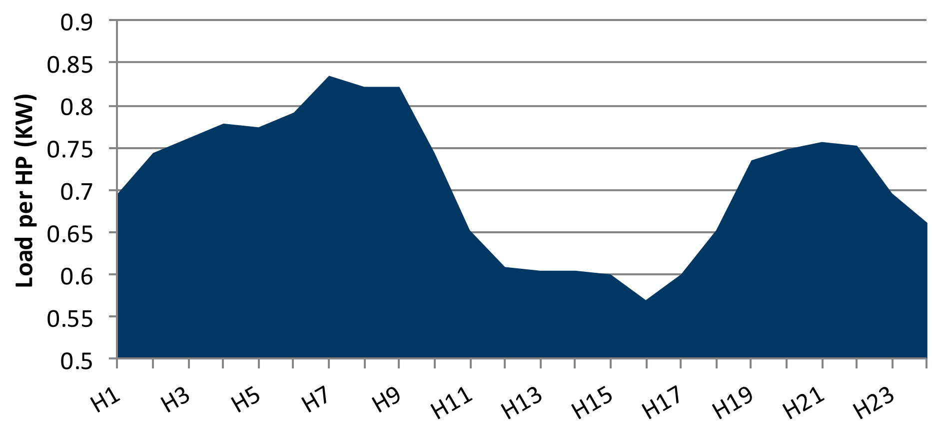
- The number of heat pumps will increase from about 2 million in 2020 to **100 million in 2050** (+400%), with a penetration of 200 HP/1000inh.
- The corresponding additional load based on ENTSOE's consumption data equals **225 TWh.**
- This projection is **in line with ENTSOE**'s between 2020 and 2040.
- **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. Their load is based on their daily load profile and a seasonality factor.

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 and hourly load



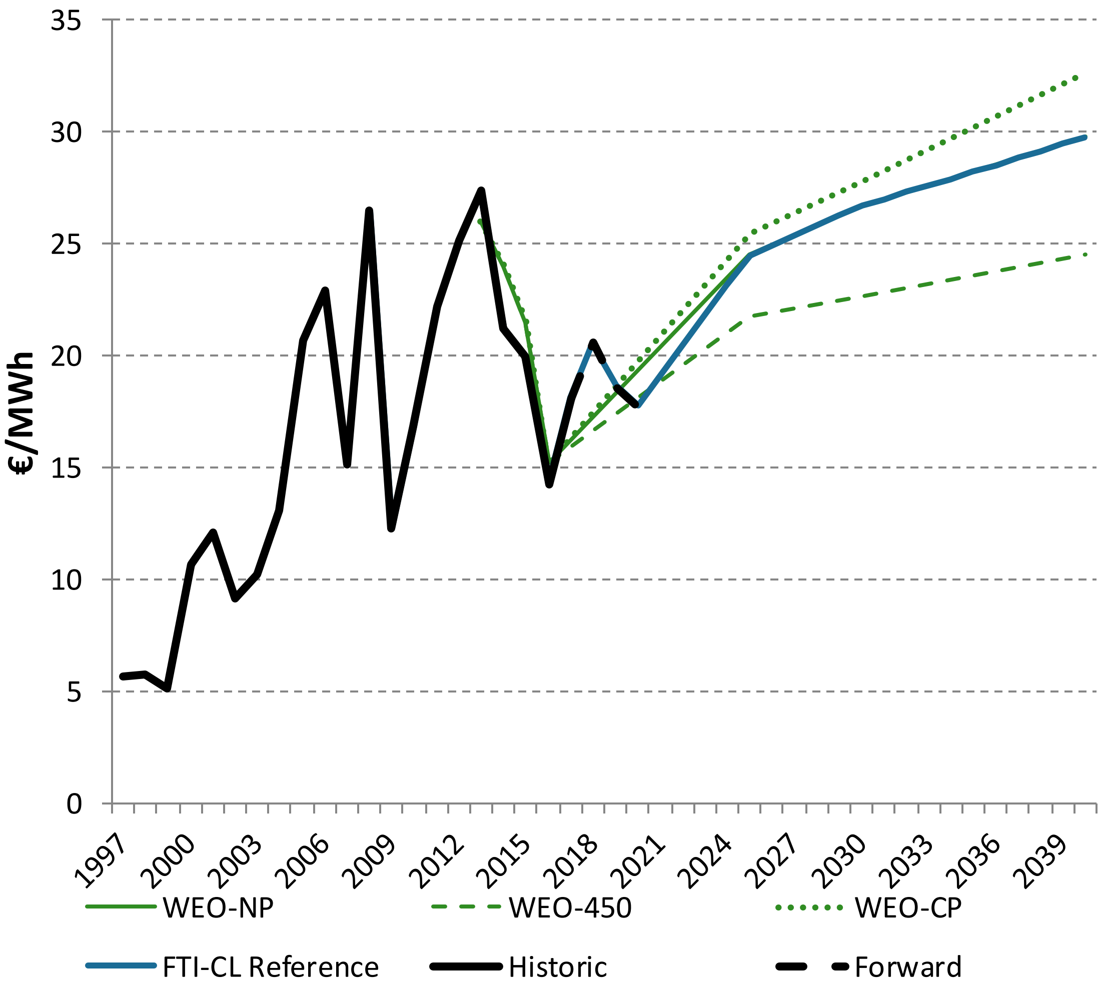
HP hourly load



Sources: FTI-CL Energy analysis, Eurelectric, ENTSOE

European Gas outlook shows an upward trend converging towards IEA WEO NP scenario

European gas outlook to 2050 (real 2017)



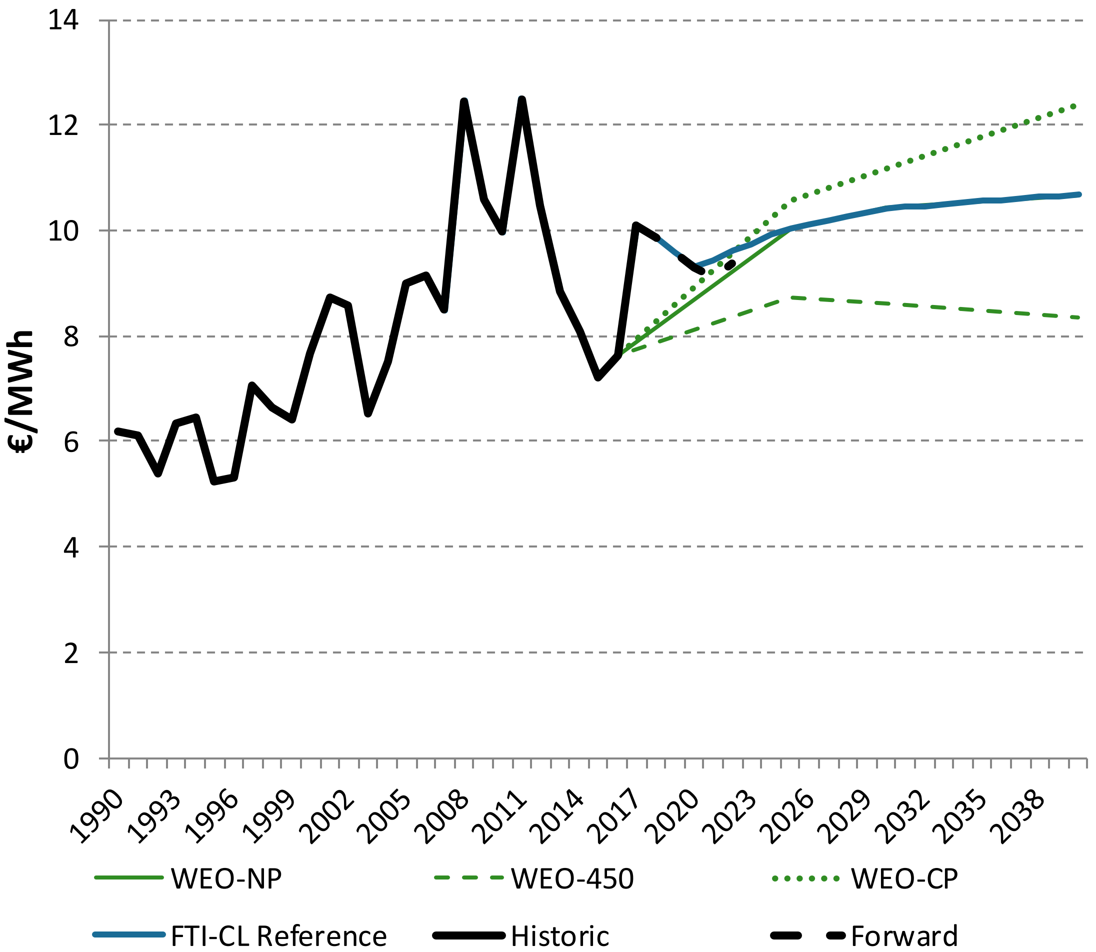
Source: FTI-CL Energy based on Bloomberg and IEA World Energy Outlook

Historic and expected gas price evolution

- European gas prices reached €11/MWh August 2016, their 5-years minimum. Since then, they increased back to c. €20/MWh in Q4 16 / Q1 17 (nearly doubling in 6-months' time), before reaching their current level of €18/MWh.
- To be comparable with European Commission and other European outlooks, our gas price outlook combines
  - Latest forward prices in the short-term and
  - IEA 2017 World Energy Outlook (WEO) scenarios. In particular, we assume that **gas prices converge to the WEO New Policies scenario by 2025.**

Coal ARA CIF outlook shows an slightly upward trend converging towards the IEA WEO NP scenario

Coal ARA CIF outlook to 2050 (real 2017)



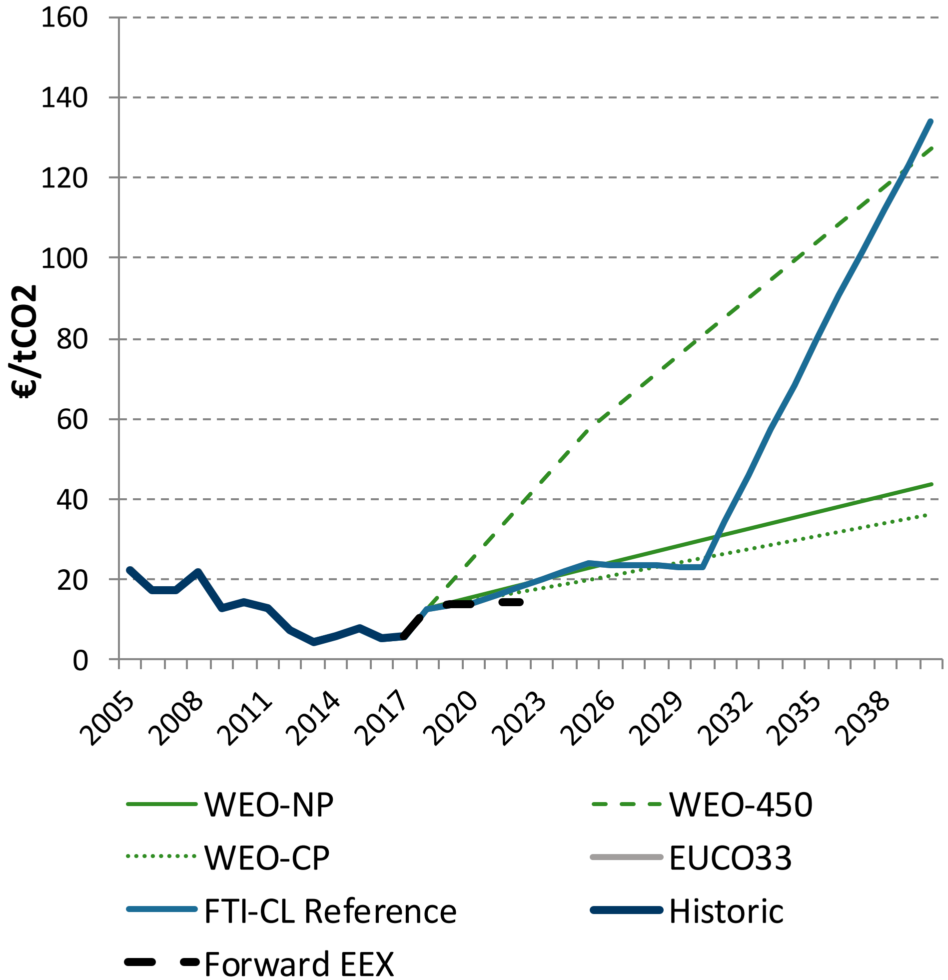
Source: FTI-CL Energy based on Bloomberg and IEA World Energy Outlook

Historic and expected coal price evolution

- The coal price reached $42/t in March-April 2016, its lowest level since 2000. Since then, the coal price increased back to an average of $80/t by end 2016, nearly doubling in 6 months' time.
- To be comparable with European Commission and other European outlooks, our coal price outlook combines
  - Latest forward prices in the short-term and
  - IEA 2017 World Energy Outlook (WEO) scenarios. In particular, we assume that **coal prices converge to the WEO New Policies scenario by 2025.**

CO2 EU ETS outlook based on EUCO33 shows an upward trend

CO2 EU ETS outlook to 2040 (real 2017)



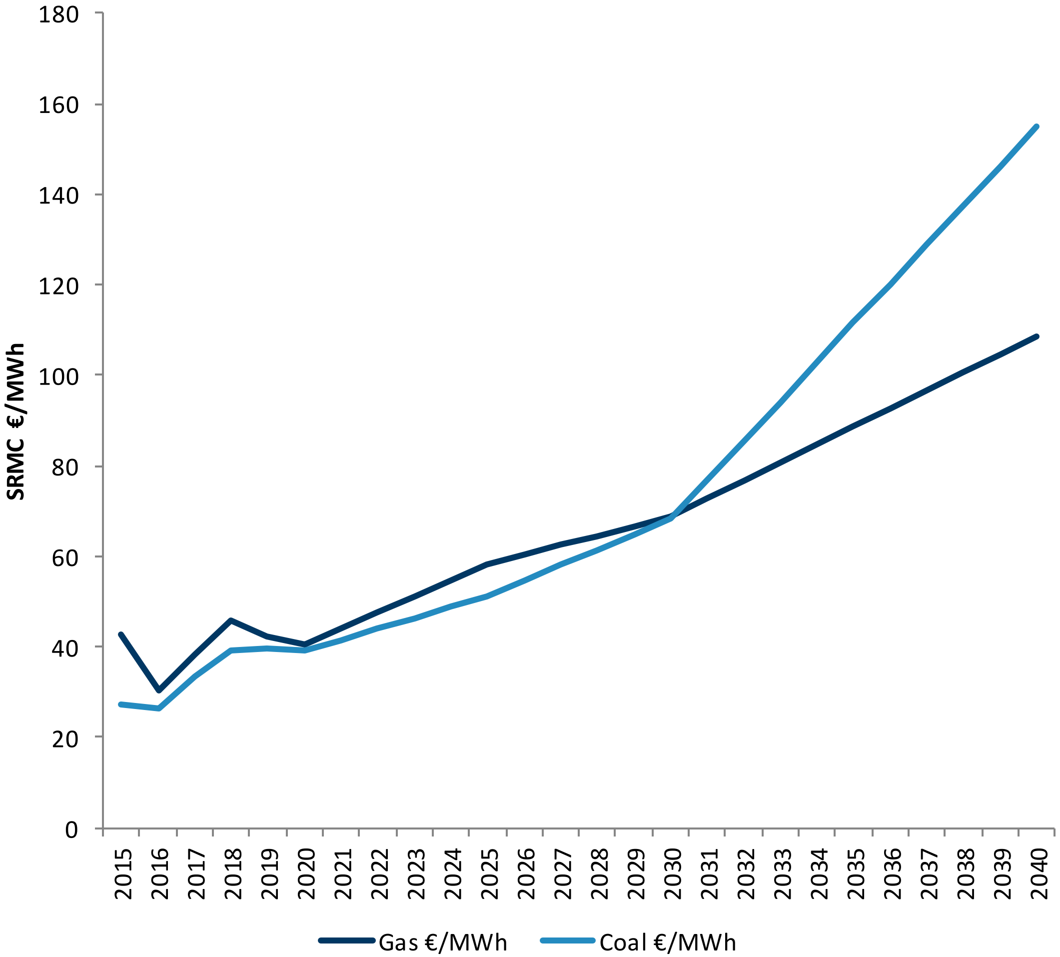
Source: FTI-CL Energy based on Bloomberg, European Commission 2016 EUCO27 scenario to 2040

Historic and expected CO2 price evolution (EU ETS)

- The EU ETS currently suffers from a surplus of emission allowances, such that the quota prices are traded at the €5-6/tCO2 level since mid 2016.
- To be comparable with European Commission and other European outlooks, our CO2 EU ETS price outlook combines
  - Latest forward prices in the short-term and
  - **European Commission's 2016 EUCO33 scenario from 2025 onwards. The EUCO33 scenario is consistent with the EU 100% decarbonisation target.** CO2 prices reaches 25€/tCO2 in 2025 and increase to 134€/tCO2 by 2040.

SRMC outlooks show that coal and gas spread remains in line until 2030 before diverging as the CO_2 price increases

FTI-CL Energy's coal and CCGT SRMCs outlook to 2040 (real 2017)



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

Sharp increase in coal SRMC resulting from high CO2 prices

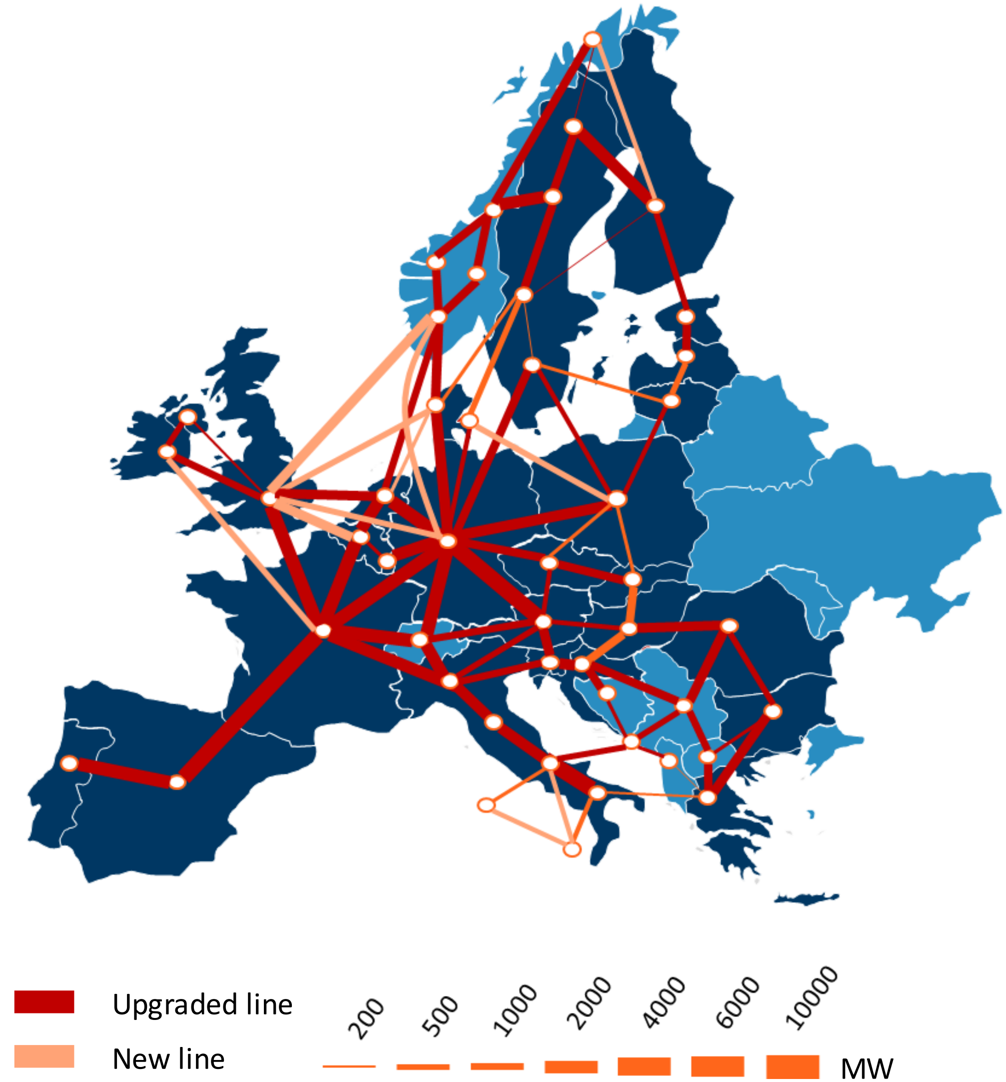
- The commodity prices assumptions presented above can be summarised in the form of Short-Run Marginal Costs (SRMC), which show the relative competitiveness of coal and gas-fired plants based on their generation costs and therefore impacts the dispatch level of the plant.
- In the medium term, **coal 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: CCGT HHV efficiency: 50%; gas carbon content: 0.183kg/kWh
Coal HHV efficiency: 36%; coal carbon content: 0.336kg/kWh

Our interconnection NTC development is based on ENTSOE TYNDP 2018 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

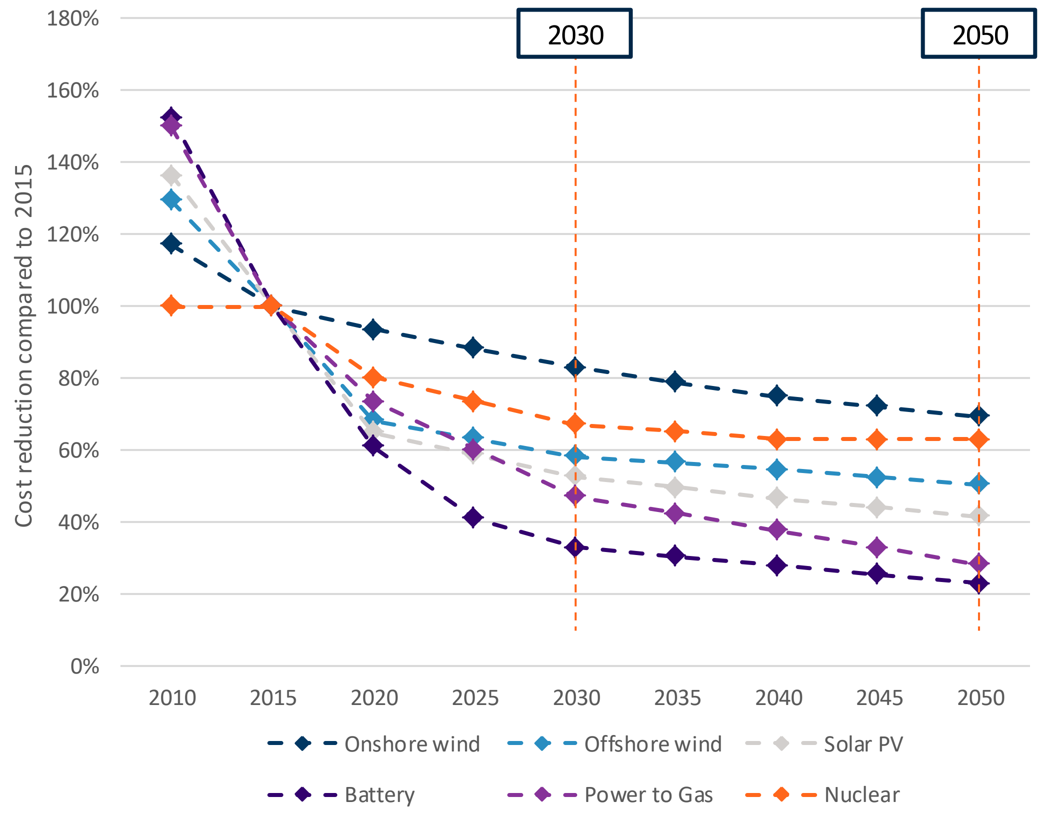
Renewable technologies and storage technologies CAPEX outlook assume a steep reduction by 2030 thanks to further learning effect

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	33%	37%
Wind onshore	17%	31%
Wind offshore	42%	50%
Solar PV	47%	59%
Power to gas	53%	72%
Battery	67%	77%

RES and storage cost reduction (%)



Source: FTI-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.

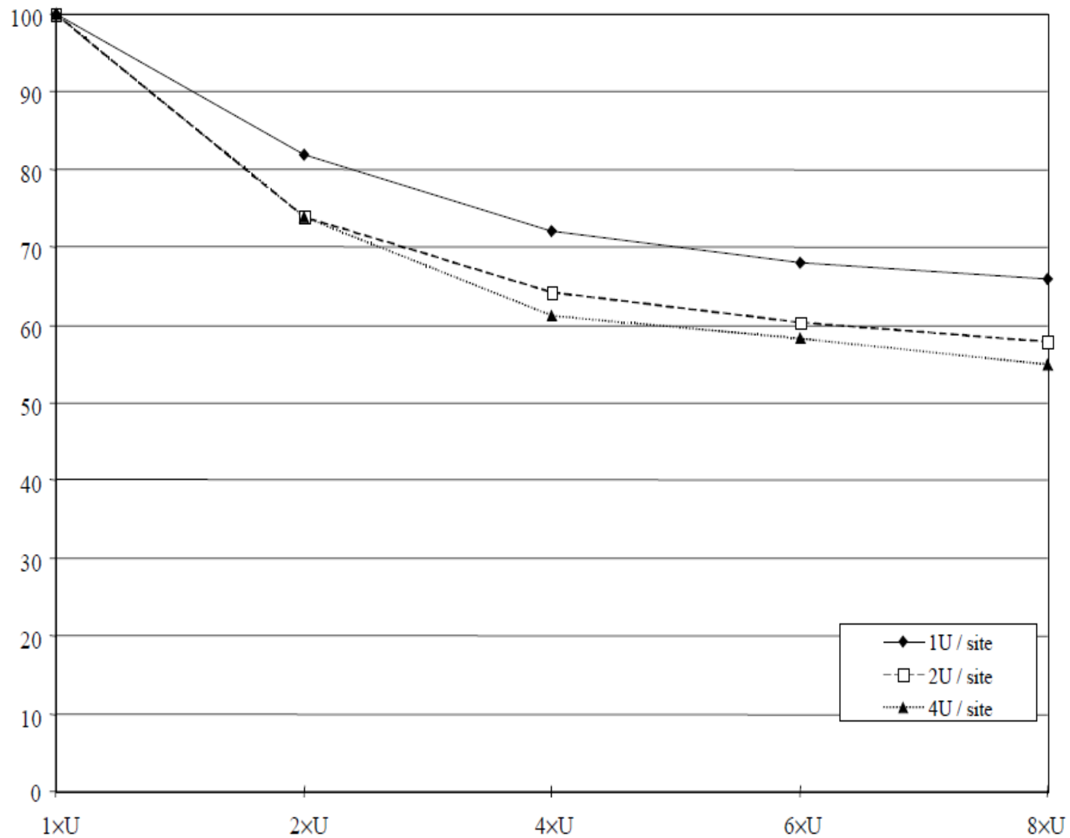
- Intense competition provoking several disruptions in the market including new chemistries development.
- Convergence toward production best practices.

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

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