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

A study commissioned by Foratom

CONFERENCE ON THE ROLE OF NUCLEAR POWER IN LOW CARBON ELECTRICITY SYSTEMS

A conference of the Chaire European Electricity Markets (CEEM), at the Université Paris-Dauphine.

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Content of the report

Study context and objectives

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

Scenario definition

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About the model

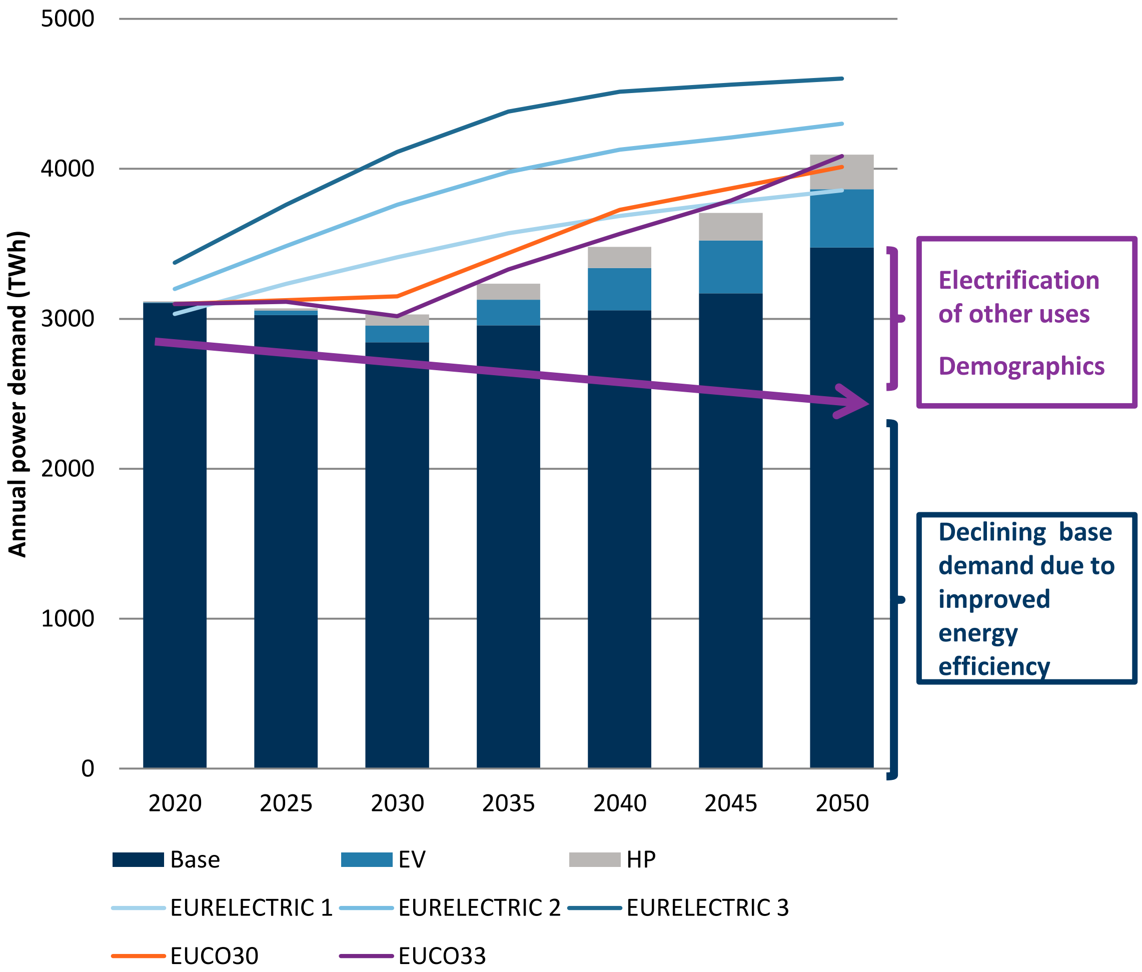
Modelling approach

- 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:
  - **90% decarbonisation** of the energy mix in 2050, compared to 1990;
  - **further electrification** of the European economy: 2050 demand forecast is projected to reach c4100TWh
- 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.

* Technology pathways in decarbonisation scenarios, Advanced System Studies for Energy Transition (ASSET), July 2018.

FORATOM's Vision demand outlook compared to benchmarks



Source: FTI-CL Energy, Eurelectric, PRIMES EUCO

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Building the nuclear scenarios

Nuclear contribution in decarbonisation

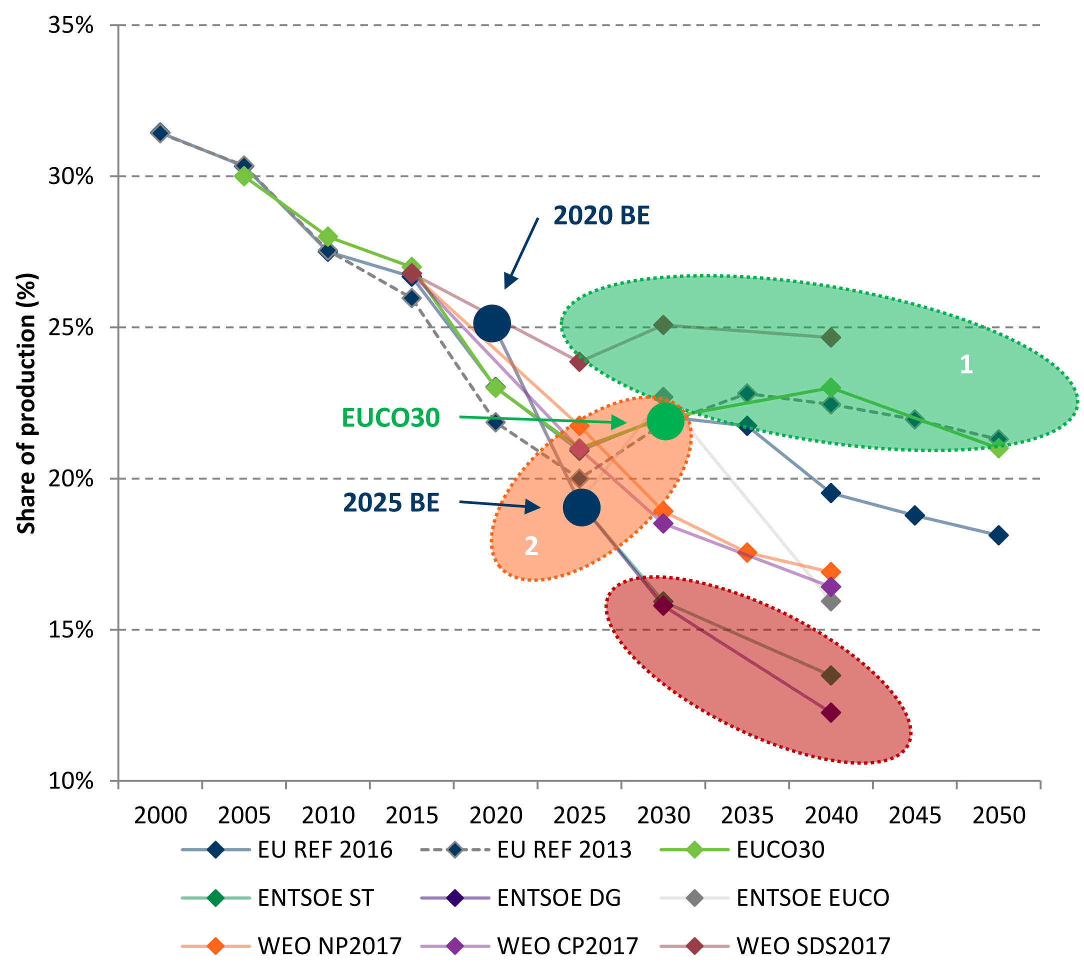
- Within the range of available scenarios that cover long term horizon, we can identify three categories of nuclear scenarios:

  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 (%)



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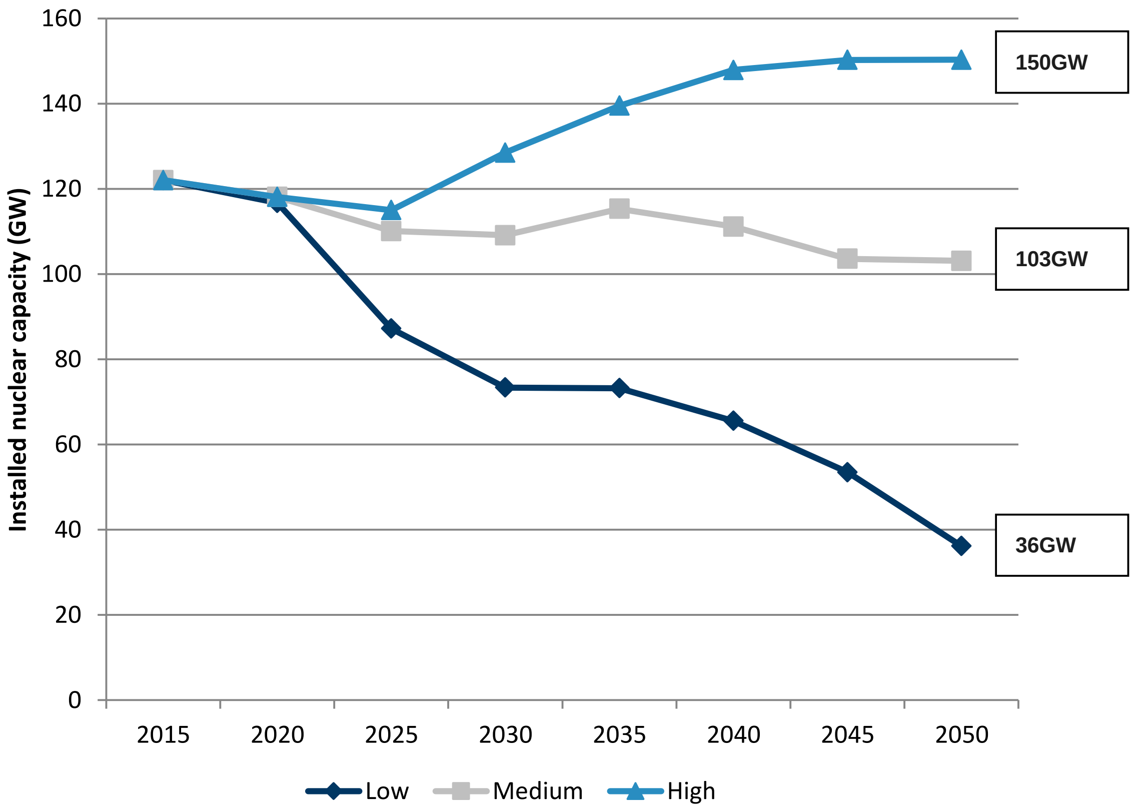
The nuclear scenarios

Delivering fact-based evidence

- The study analyses the different scenarios using a multi-criteria analysis framework to capture their impact on the main dimensions of Europe's energy policy:
  - security of supply;
  - Sustainability; and
  - economics.

- The Vision 2050 study aims at **delivering fact-based evidence** in response to these key dimensions 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.

EU-28 nuclear installed capacity outlooks (GW)



Source: FTI-CL Energy analysis based on FORATOM inputs

Modelling results and conclusion

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Results - Security of supply [1/5]

Installed capacity outlook in the Low scenario

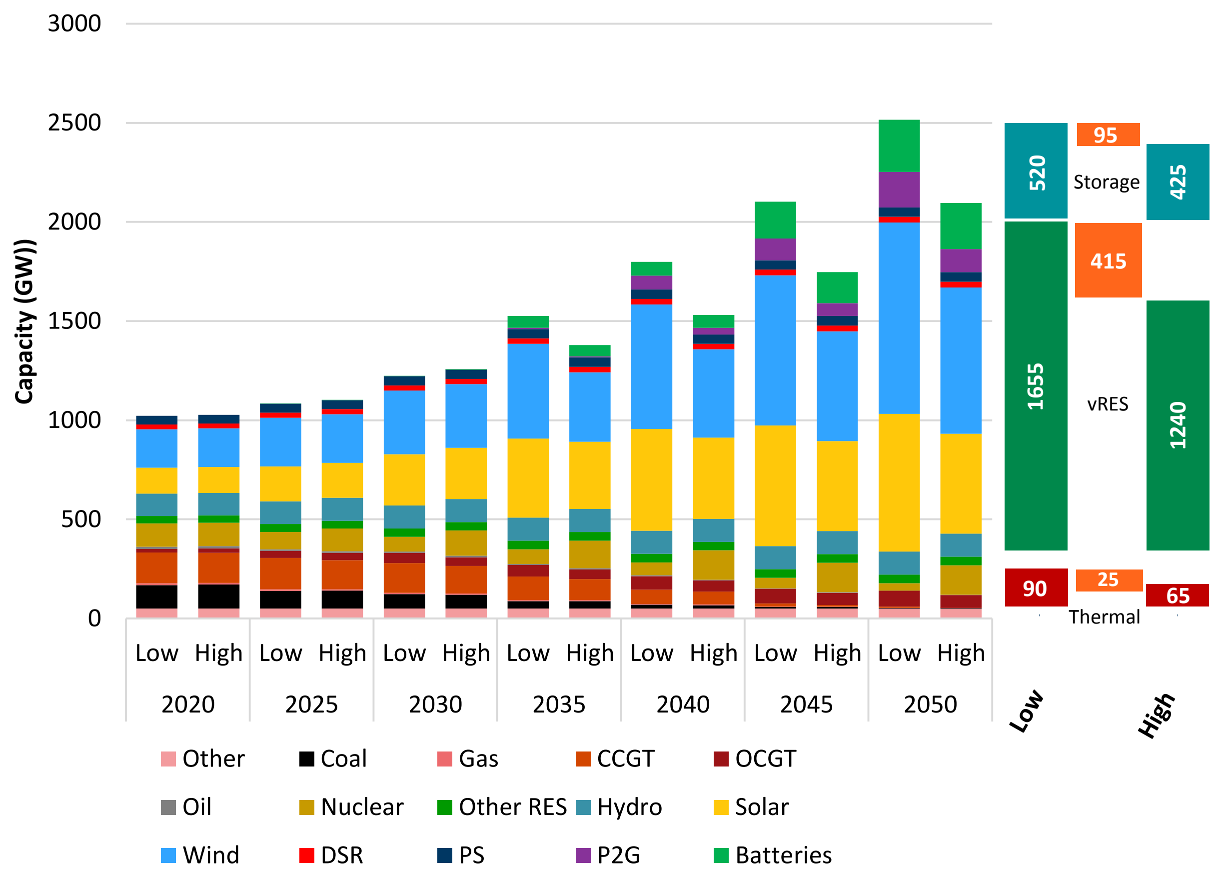
- In the low scenario, 1345GW of new RES are installed reaching a total of 1655GW including 695GW of solar and 960GW of wind.
- Additionally, 520GW of new flexible capacity is installed, of which 265GW of batteries and 180GW of Power to Gas.

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.

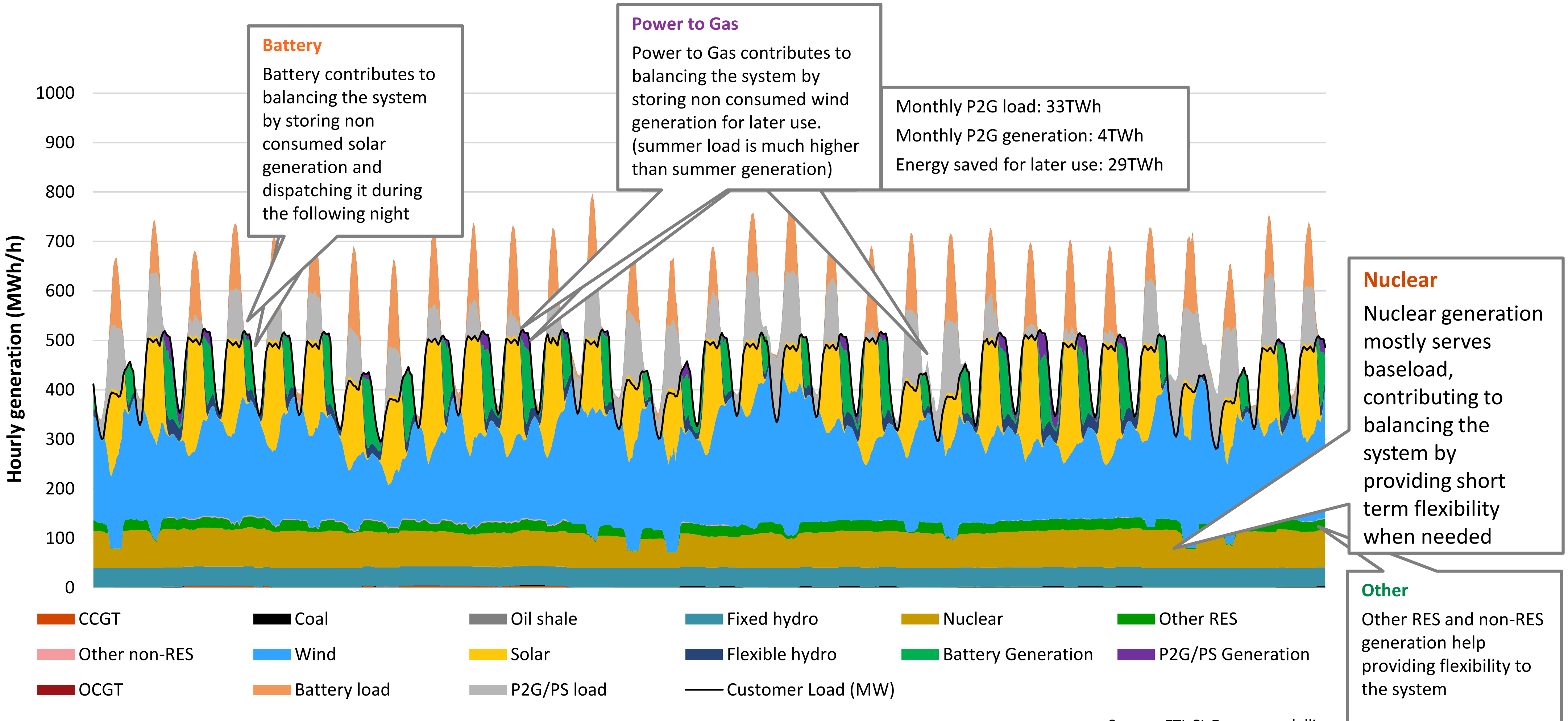
Low and High scenario capacity outlook



Source: FTI-CL Energy analysis

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

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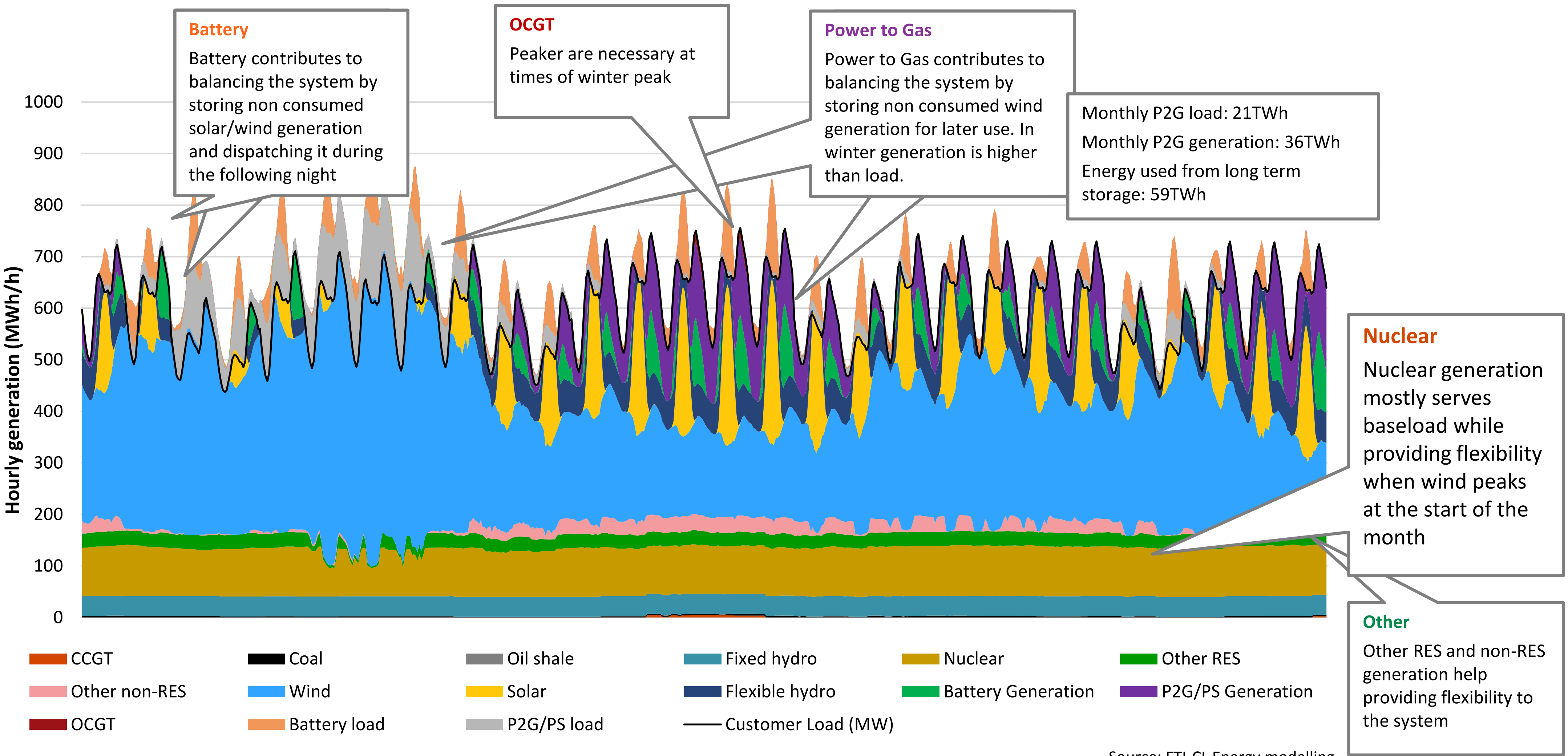
In the winter in 2050, nuclear continues to operate baseload most of the time as excess RES production is absorbed by storage and P2G

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

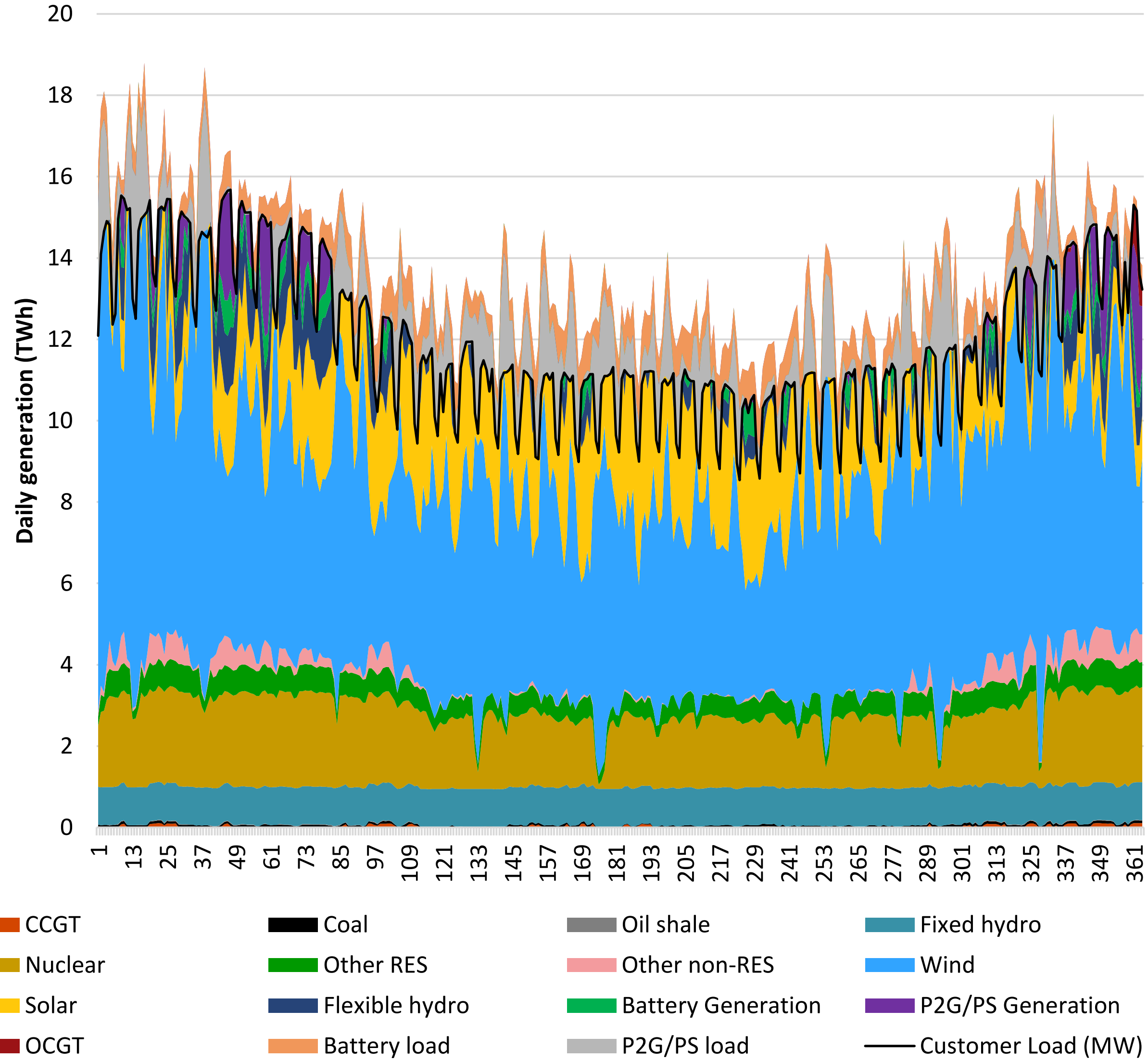
Nuclear contributes to providing flexibility and baseload power to the system by cycling at different times:

- **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

Results - Security of supply [5/5]

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 440 GW of batteries and seasonal storage such as Power2X in 2050 in the Low scenario)

Increased reliance on thermal generation

- By closing nuclear capacity instead of investing in its long-term operation, **2790TWh of additional fossil fuel based thermal generation will be needed** in the short to medium term, representing a **+20% 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 6500TWh**, pushing up Europe's dependence on fossil fuels to an equivalent of +36% in gas consumption and +18% in coal consumption between 2020 and 2050.

Results – Sustainability [1/2]

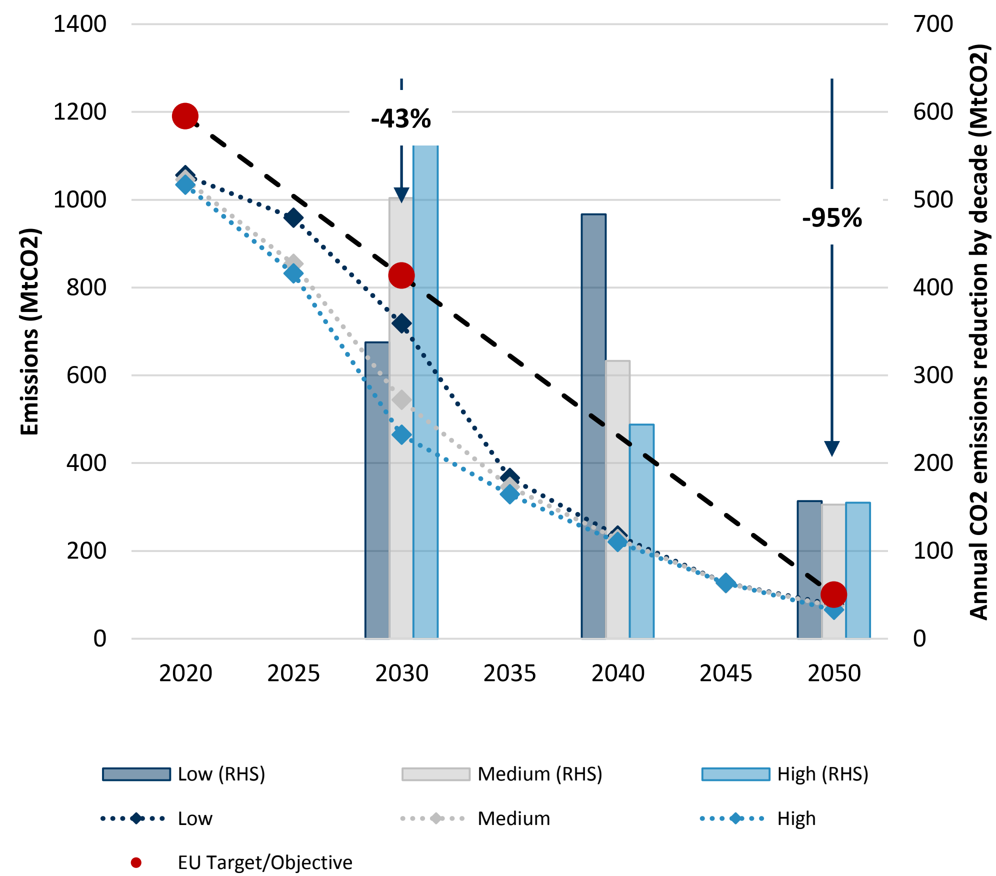
Anticipated nuclear closure and limited new nuclear investments in the low scenario would materially increase total emissions over 2020-2050:

- 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 CO_2 emissions or **17% of total CO2 emissions from the power sector** over 2020-2050.

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

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



Note: Emission from power sector do not include emission from heat

Source: FTI-CL Energy analysis

Results – Sustainability [2/2]

Reduced CO2 emission

- Anticipated nuclear closure and limited new nuclear investments in the low scenario would materially increase total emissions over 2020-2050 (c2300MtCO2 or +17%), especially before 2035.

Environmental footprint

Air and water

- Pollution would be reduced by c14%, including a 15% reduction in SO2 emissions, 9% in NOx and 18% in PM

Land use

- The amount of land needed for power generation would be about 15800km2 lower by 2050 – equivalent to half the size of Belgium – 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 66TWh of additional curtailed energy in 2050 compared to the high nuclear scenario (a +160% increase)

Results – Economics [1/2]

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.

CO_2 emissions outlook from the power sector

% 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%

Source: FTI-CL Energy analysis, E3M

Results – Economics [2/2]

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 **350bn€** (real 2017) 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 **€960 billion in 2050** compared to the high scenario. This represents 29% 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 **160bn€** (real 2017) by 2050.
- Pollution would be reduced by c14%, including a 15% reduction in SO_2 emissions, 9% in NO_x and 18% in PM

Conclusions

Important contribution of nuclear to the transition towards a decarbonized European power system:

- **In the short to medium term**: Nuclear LT Operation helps (i) ensure compliance w/ EU emission targets (ii) avoids temporary increase of emissions (iii) avoids locking in fossil fuel investments;
- **In the longer term**: nuclear supports vRES by (i) providing proven carbon free flexible power (ii) reducing reliance on yet to be proven storage technologies.

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

- New nuclear power needs to **demonstrate significant cost reductions** to succeed in liberalised European power markets.
- **Timely development & cost reduction of storage technologies as well as flexible operation of nuclear** critical to ensure nuclear - vRES complementarity.
- To address the high vRES environment challenges**, the market design should (i) reward dependable & flexible sources system value and (ii) provide stable long-term investment signals.**

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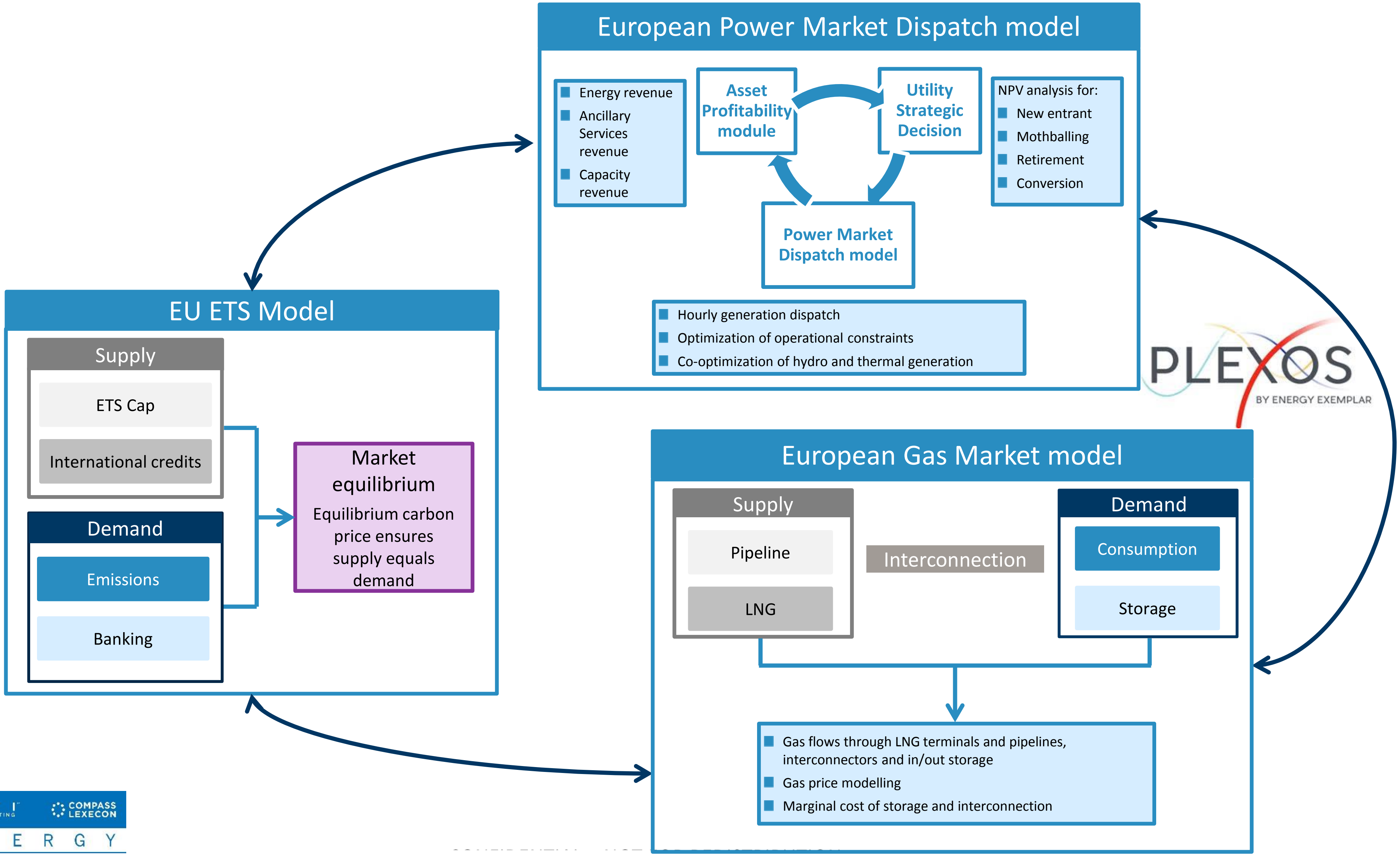
Appendix 2: FTI-CL Energy modelling capability

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



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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

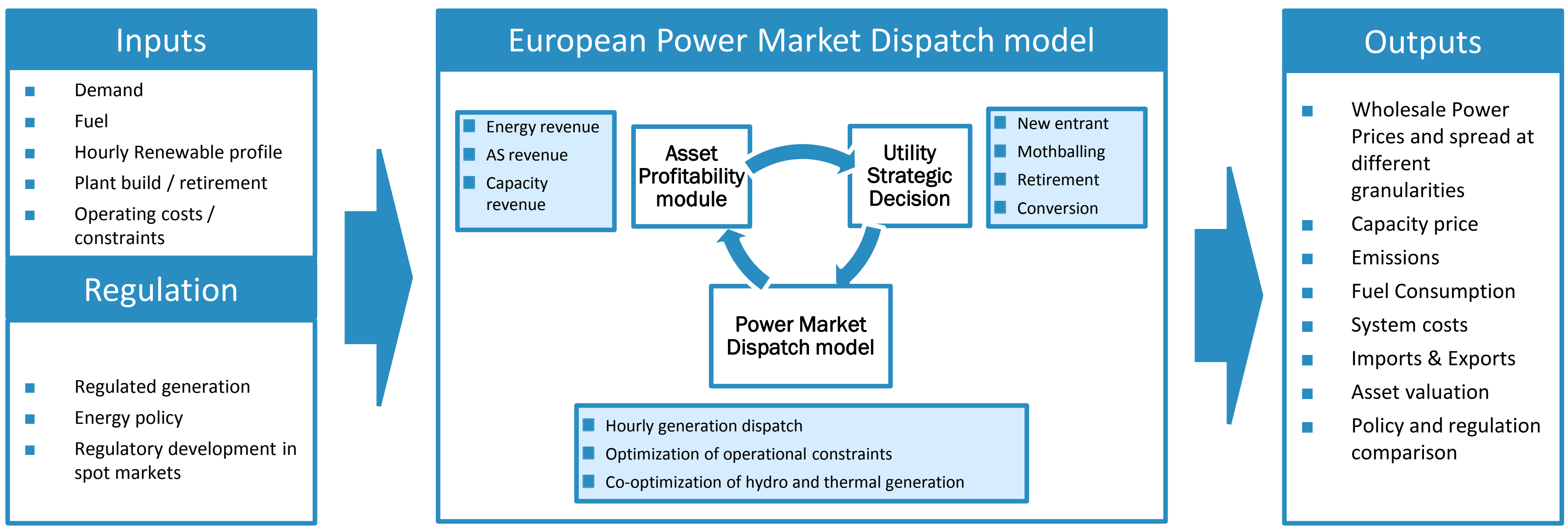
FTI-CL Energy’s power market model relies on a dispatch optimisation software with detailed representation of market fundamentals

Dispatch optimisation based on detailed representation of power market fundamentals

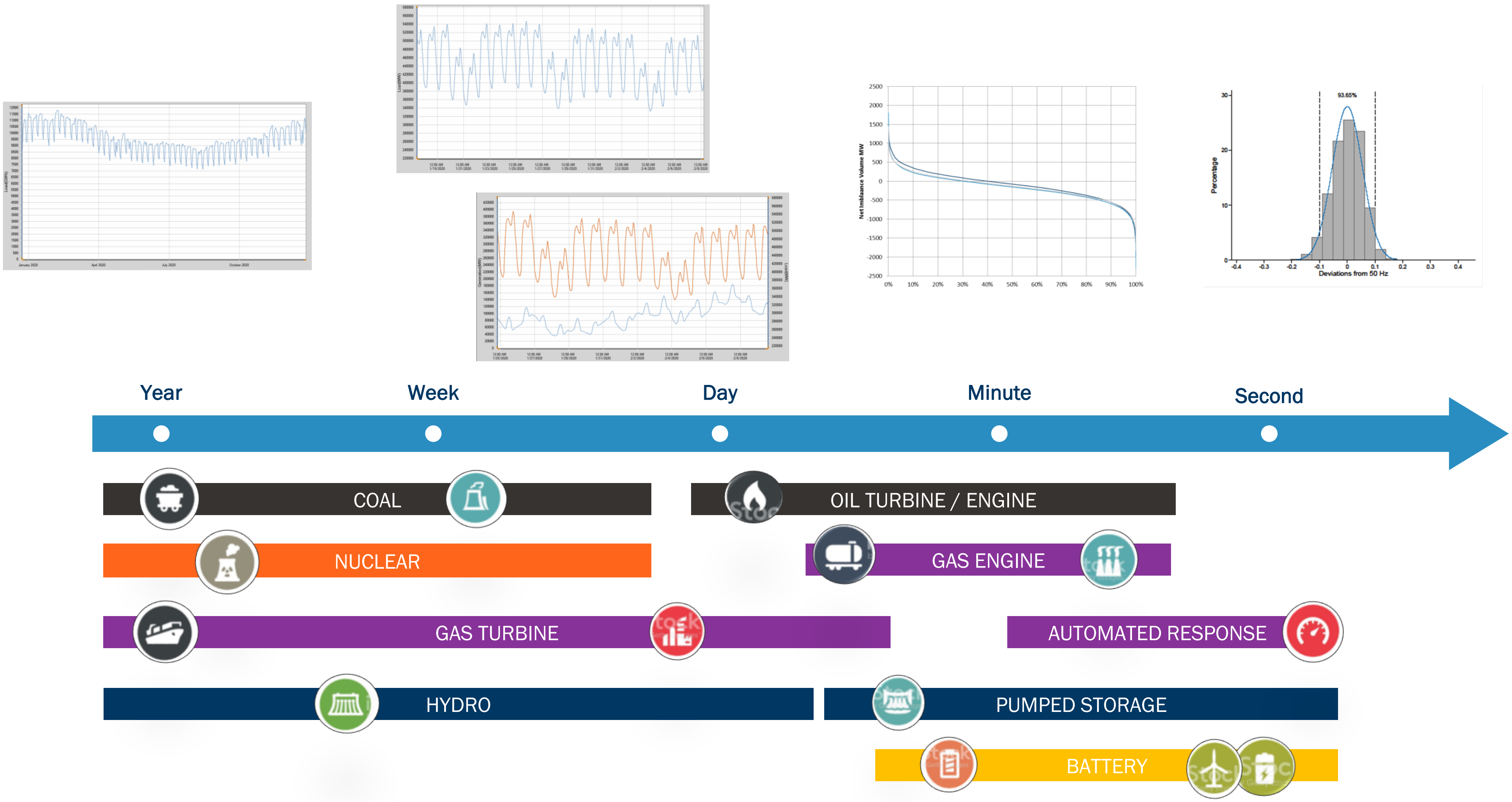
- At the heart of FTI-CL Energy’s market modelling capability lies a dispatch optimisation software, Plexos®, based on a detailed representation of market supply and demand fundamentals at an hourly granularity. Plexos® is globally used by regulators, TSOs, and power market participants.

- 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



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)
CO_2 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)

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