FORATOM
THE VOICE OF THE EUROPEAN NUCLEAR INDUSTRY

## FORATOM TAKEAWAYS FROM THE UPDATED

# PATHWAYS TO 2050: "ROLE OF NUCLEAR IN A LOW-CARBON EUROPE" REPORT


## FORATOM ANALYSIS

NOVEMBER 2021

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# TABLE OF CONTENTS

# 1. INTRODUCTION

## 1.a Context

In 2018, FORATOM commissioned a report from consulting firm Compass Lexecon (CL) in order to assess the role that nuclear could play in the long-term and deep-decarbonisation scenarios. This report contributed successfully to FORATOM's credibility in the debates with the European Commission (EC), as it provided useful insights on how nuclear can play its part in decarbonisation efforts. One of the main achievements was the reference made to the report in the EC's long-term strategy in-depth analysis. It established the study as a reliable source of information for all of the different EC scenarios.

Since then, FORATOM considered it necessary to request an updated version, mainly as a result of two major changes:

1. With Brexit, all of the EC's new long-term scenarios now consider the EU27. A request was made to comply to this new perimeter.
2. Updated decarbonisation targets were announced for both 2030 (with an increase from 40% GHG emission reductions to at least 55%) and 2050 (from 80 to 95% GHG emission reductions to net zero emissions).

In addition, with the above-mentioned changes, further analyses were performed, mainly arising from the latest initiatives by the EC (i.e. the European Green Deal), such as:

- explicit modelling of low-carbon hydrogen power consumption
- explicit modelling of demand flexibility
- updated EU demand outlook
- updated thermal plant phase-out policies
- updated RES development in line with National Energy and Climate Plans (NECPs)
- updated costs of RES and storage technologies

## 1.b Short history of the project

The project started to take shape at the end of 2017, with the goal of creating an overview of the long-term future of the nuclear sector, while taking into consideration the latest available forecasts at EU level for the power sector. Released in November 2018, the report presented the results of a detailed modeling for different aspects such as:

- electrification trends
- energy system flexibility
- security of supply
- carbon intensity

An updated analysis was presented in January 2021 with the updated "Pathways to 2050: Role of nuclear in a low-carbon Europe".

[1] In-depth analysis in support of the commission communication COM(2018) 773.

# 2. DESCRIPTION OF THE METHODOLOGY

The aim of the current document is to:

- review the Compass Lexecon conclusions relating to the different topics identified,
- compare the Compass Lexecon scenarios and conclusions with the EC Impact Assessment (SWD(2020) 176 final), and
- compare the Compass Lexecon sustainability conclusions with the Joint Research Centre's technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation') and enhance some of the results using FORATOM findings on sustainability issues (i.e. land-use – external costs or resource use).

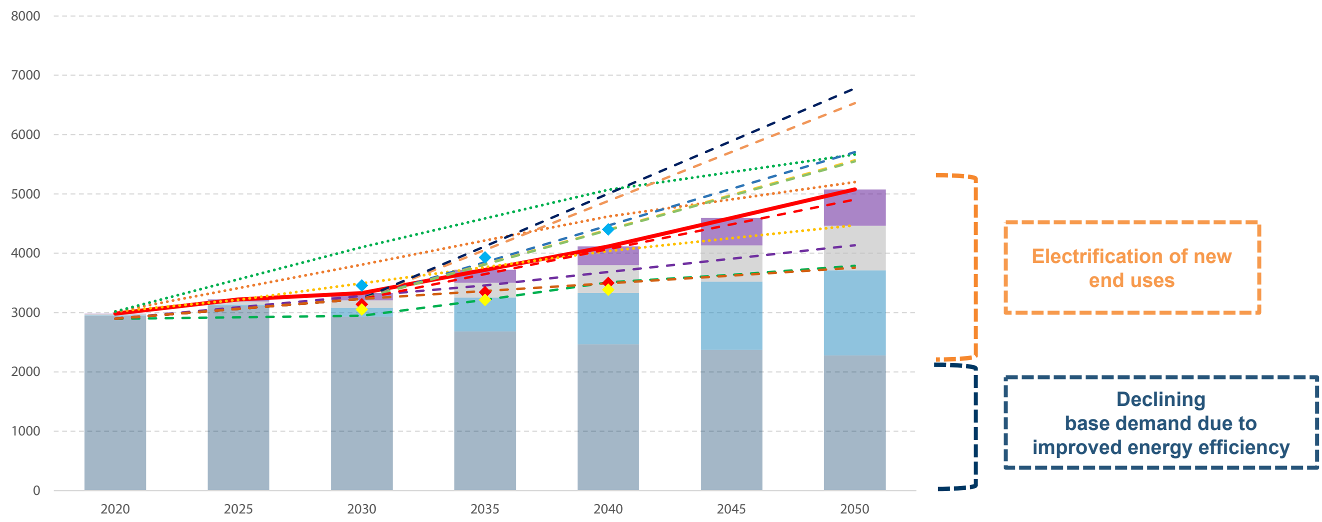
# 3. DESCRIPTION OF THE ASSUMPTIONS

## 3.a Electricity demand

This section provides an overview of the forecasted power demand up to 2050 and draws some analysis from the two nuclear scenarios used by CL against the proposals from the Impact Assessment accompanying the EC's communication on "Stepping up Europe's 2030 climate ambition" (SWD(2020) 176 final).

Considering the different scenarios available at EC level, CL's forecasts for electricity demand up to 2050 are the following:

**Graph 1: EU27 + UK Power demand forecasts 2020-2050 (TWh)**




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

Source: CL 2021 report

Three main reports were used as central assumptions underpinning the modelling of electricity forecasts:

- Eurelectric's Decarbonisation pathways study, 2018
- European Commission's EUCO scenarios, 2016
- European Commission's long term strategy scenarios, November 2018

The model developed by CL refers to EUCO33, a scenario that builds on the EUCO30 scenario and explores a more ambitious energy efficiency target of 33% to 2030.

### Comparison with the EC Impact Assessment

Since 2018, the European Commission has published an Impact Assessment accompanying the EC communication on "Stepping up Europe's 2030 climate ambition" (SWD(2020) 176 final) which draws policy scenarios whereby the EU's Emission Trading Scheme (EU ETS) may be able to achieve complementary Greenhouse Gases (GHG) abatement compared to existing policies in place in the EU-27:

- increased GHG reduction targets for 2030 from 40% to 55%
- increased GHG reduction targets for 2050 from up to 95% to net zero

A consequence of increased GHG reduction targets will be an increase of the share of renewables in gross final energy consumption in 2030 (currently 32%), along with a higher energy efficiency target (currently 32,5%)[2] .

In the EC's Impact Assessment Scenario overview, four policy scenarios (See Box 1) have been developed. These policy scenarios take into account an accelerated growth trend for the share of renewable energy sources (RES) until 2030, which will help to achieve the new ambitions envisaged of a 55% reduction in GHG emissions by 2030.

The ALLBNK scenario, the most ambitious scenario in terms of GHG reductions, foresees the inclusion of all aviation, navigation, road transport and buildings within the EU Emissions Trading Scheme (ETS). Given that green hydrogen and e-fuels are counted for within the RES share, this scenario predicts the largest share of renewables in the electricity mix[3].

Comparing the ALLBNK and the CL's high nuclear scenario – the latter being a scenario in which the long-term operation of most of the existing nuclear reactors is considered and additional new capacities are commissioned (for more info, see section 3.b) – we note the following:

- Both scenarios help to achieve a +60% share of renewables in electricity consumption by 2030. In the ALLBNK scenario, the share of RES rises to 67% by 2050. This is comparatively less than the 79% share of RES in the 2021 CL high nuclear scenario.
- In the EC's Impact Assessment, emission abatement occurs both in the supply of electricity and in its end uses. As an example of end-uses abatement, the carbon price provides incentives to end-users to shift to low-carbon heating applications. In the CL report, the power sector acts efficiently in supporting direct and supply led carbon mitigation at a lower carbon price[4].

[2]DIRECTIVE (EU) 2018/2001 - The Clean Energy Package also incorporates the ETS Directive and EFS Regulation.
[3]With the ALLBNK scenario: 67% of RES in electricity is achieved in 2030 (representing 40% of RES in final energy consumption) - A higher level that the FORATOM-CL study.
[4]In the CL model, the amount of nuclear generation produced in 2050 stands at 950 TWh while the EC Impact Assessment foresees a lower share of nuclear generation in 2050.

### Table 1: EC Impact Assessment – Policy Scenario

Box 1: EC scenarios from (SWD(2020) 176 final)

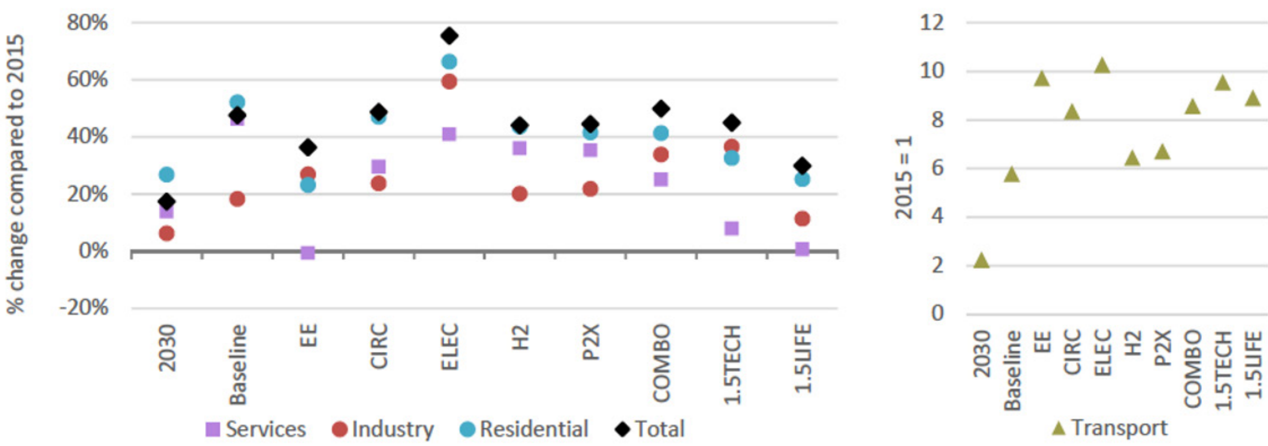
- **BSL**, achieving the existing 2030 GHG, RES and EE EU targets
- **REG**, a regulatory-based measures scenario that achieves around a 55% reduction in GHG emissions. It assumes a high increase in ambitions relating to energy efficiency, renewables and transport policies, while keeping the EU ETS scope unchanged. This scenario thus does not expand carbon pricing and relies mostly on other policies
- **CPRICE**, a carbon-pricing based scenario that achieves around a 55% GHG reduction. It assumes the strengthening and further expansion of carbon pricing, be it via the EU ETS or other carbon pricing instruments, to the transport and building sectors, combined with low intensification of transport policies. It does not intensify energy efficiency and, renewable policies
- **MIX**, which follows a combined approach of REG and CPRICE, and achieves around a 55% reduction in GHG, both expanding carbon pricing and moderately increasing the ambition of policies, but the latter to a lesser extent than in REG;
- **ALLBNK,** the most ambitious scenario in GHG emissions reduction, based on MIX and further intensifying fuel mandates for aviation and maritime sectors in a response

Source: EC Impact Assessment (SWD(2020) 176 final)

**Key comparative highlights:**

- Comparing CL's pathway in relation to power demand (see Graph 1) with the scenarios proposed by the EC, it can be assumed that the consultant stands in the mid-range of EC power demand forecasts. CL's power demand assumption for 2030 is similar to the EC scenario at around 3000 TWh/year.
- For 2050, CL's power demand forecast (4 900TWh including the UK with 498 TWh) shows some divergence from the most ambitious of the EC's long-term strategy scenarios in terms of GHG reduction (scenario EC 1,5Tech) and to the EC P2X scenario with e-fuels. Both EC scenarios foresee power demand rising up to 6 700 TWh – 7 000 TWh. In those two specific scenarios, electricity demand forecasts for 2050 are higher as a result of the decline in total energy efficiency (see Graph 2).

### Graph 2: Electricity demand change (2050 compared with 2015) in the EC's Long-Term Strategy




Source: European Commission

- The 2021 CL report has been updated by taking into account the contribution of hydrogen to power demand in 2050 as provided for by both EUCO and Eurelectric[5]. Hydrogen is an energy carrier that will be expanding in the future and its impact on the 2050 final electricity demand will result from investments in new capacities taking place in the EU (or outside), and from dedicated incentives and policy approaches, notably with the revision of the Renewables Directives.

## 3.b The nuclear scenarios

In the CL 2021 report, the difference between the two scenarios provides an opportunity for policy makers to assess the implications of investment decisions to take place between 2020 and 2050 in the EU. The difference between the two scenarios also helps describe changes in market behaviors[6].

Two scenarios have been defined in the CL study when it comes to the level of installed nuclear capacities in the EU-27 + UK: a low nuclear scenario and a high nuclear scenario. In both scenarios, power generation capacities can be understood as net of new build capacities after capacity closures. In the low nuclear scenario, estimations allow for the end of licensing lifetime or earlier than planned closure. In the high nuclear scenario, several long-term operation (LTOs) extensions are awarded and additional new capacities (including c. 22 GW of SMR and <1 GW of Gen-IV) are commissioned, replacing thermal baseload generation.

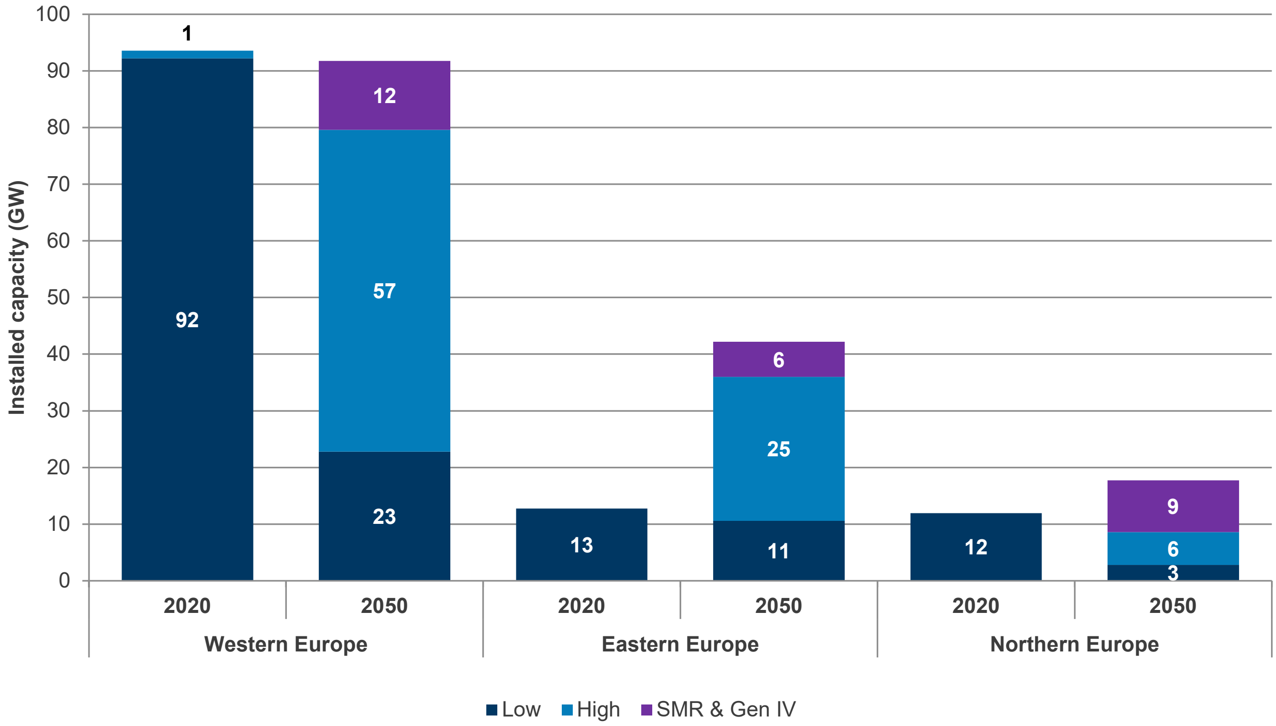
In the short term both scenarios show that nuclear capacity drops by 2 GW to a total of 25 GW by 2025. This is mostly due to the nuclear phase-out plans of some countries (e.g. Germany and Belgium).

After 2025, the two CL scenarios show diverging installed capacity visions.

- Low Nuclear Scenario: No Long-Term Operation and limited new build
  - U-27 nuclear capacities stand at 28 GW in 2050 (36 GW including the United Kingdom).
- High Nuclear Scenario: Long-Term Operation and new build
  - *EU-27 nuclear installed capacities stand at 132 GW in 2050 or 152 GW when including the United Kingdom.*

*Comparing the two scenarios for the EU-27 therefore indicates a difference in nuclear installed capacities of 104 GW in 2050 or 116 GW when including the UK.*

**Graph 3: Installed nuclear capacity by scenario and region (GW)**




Source: CL 2021 report

The CL model provides as output different sets of market responses to energy system capacity evolutions under the assumption that all power plants operate in a rising interconnected power market, up to an interconnection capacity of 439 GW in 2050[7]. Interconnections are based on the ENTSOe Ten-Year Network Development Plan 2020[8].

Key report highlights: The difference between the two scenarios in 2050 corresponds to 104 GW of net nuclear capacity installed in the three regions of Western Europe, Eastern Europe and Northern Europe (116 GW when including the UK). One similarity between the two scenarios is that both impact grid system management, in particular the low scenario where limited nuclear new build and no LTO takes place (see section on transmission and distribution costs).

**Key report highlights:** The difference between the two scenarios in 2050 corresponds to 104 GW of net nuclear capacity installed in the three regions of Western Europe, Eastern Europe and Northern Europe (116 GW when including the UK). One similarity between the two scenarios is that both impact grid system management, in particular the low scenario where limited nuclear new build and no LTO takes place (see section on transmission and distribution costs).

# 3.c Power system flexibility

**Definition of flexibility:** In power generation, flexibility can be defined as the ability of the power system to remain stable, while coping with the variability of power demand and supply at all times.

Flexibility is a key parameter in economic modelling that helps to assess whether or not integrating more (or less) variable RES is economically viable. Without any flexibility constraints, balancing and re-dispatching costs are down to zero and the electricity total power generation system costs are equivalent to the marginal electricity only costs.

The CL study focuses on the energy arbitrage flexibility, meaning that sudden changes in demand (resp. supply) need to be either compensated for by a reaction of supply (resp. demand), or adjusted through storage (see Graph 4 for energy arbitrage capabilities of several technologies). To do so, several assumptions are taken with respect to the demand side's flexibility (exogenous) while endogenous investment in three flexible low-carbon supply technologies are allowed: power-to-gas, batteries and fossil fuel (mainly gas) with carbon capture and storage (CCS). In the model, all low-carbon baseload technologies do operate in energy markets while taking into account seasonal variations.

### New assumptions in the 2021 edition:

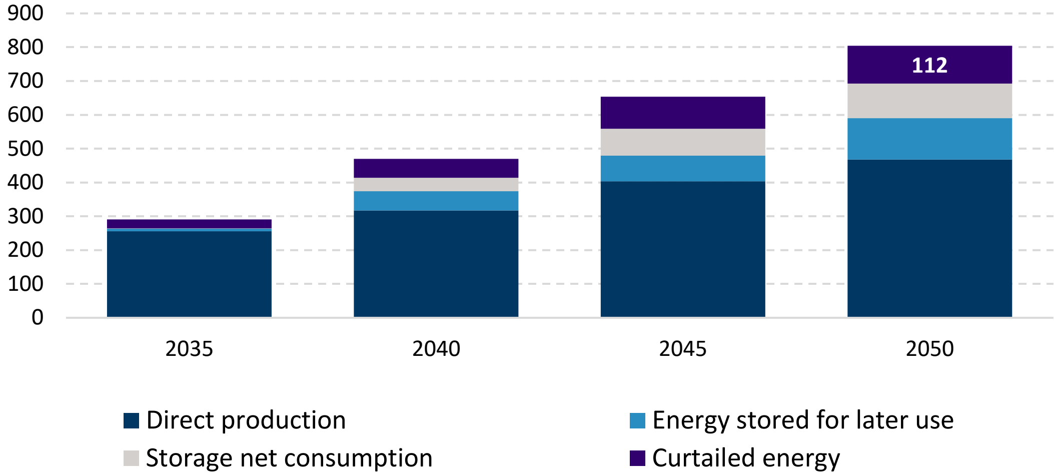
On the demand side, two flexibility provisions have been considered in the 2021 edition with:

1. Hydrogen production acting as a flexible energy carrier when consumed in industries. Equivalent flexibility reserves of between 28 GW and 60 GW can be activated in situations where the hydrogen production load factor is adjusted downwards (from 75% to 60%) or stopped for a shorter period (see 4.d).
2. Heating and cooling pumps: In 2050, 100 million heat pumps fitted with dynamic controls help modulating final electricity consumption assuming a 2 to 3 hours response delay.

Overall, between the high scenario and the low scenario, 320 TWh of wind and solar power is being generated, providing upward or downward flexibility system needs (see next page Graph 4) and maintaining the stability of the system. The optimization of the model also leads to energy curtailment as illustrated in the graph below. Energy curtailment corresponds to an energy loss.

[5]Joint Research Centre - Towards Net zero emission in the EU power system in 2050, 2020 – See Page 5.
[6]From an economic perspective, the model translates capacities into cost-benefits with reference to the Net Present Value of investments using an expected rate of return of 5% real (equivalent to the cost of capital).
[7]Model outputs: Wholesale Power Prices and spread at different granularities, Capacity price, GhG Emissions, Fuel Consumption, System costs, Imports & Exports, Asset valuation.
[8]ENTSOe 10 Year Network Development Plan, January 2021.

## Graph 4: RES (wind, solar) based power generation differences between Low and High scenarios (TWh)




Source: CL 2021 report

### Energy storage capacity expansion and implications

In 2050, battery storage capacities provide both stationary and EV related applications. Between 140 GW (High S.) and 183 GW (Low S.) of battery storage is added (starting in 2035) in addition to P2G capacities of between 90 GW (High S.) and 143 GW (Low S.). In the CL report, the average storage capacity per EV is 30 KWh in 2050, similar to IRENA forecasts.[9]

The high nuclear scenario would require no additional batteries nor CCS and only 6 GW of power-to gas by 2050. With regards to power-to gas (P2G), new investments are almost ten times greater (53 GW) in the low nuclear scenario, along with the commissioning of 43 GW of additional battery storage and 2 GW of CCS. In terms of electricity generation, the low scenario is also more carbon intensive as it yields lower capacity factors for nuclear plants and higher capacity factors for all thermal generation, including the older and more carbon intensive plants.

In addition, investments in flexibility do not prevent curtailment from happening. The underlying rationale is that given the cost of flexibility and the decarbonation constraints, it is more economical to reduce or curtail some of the energy produced than to have a demand (resp. supply) following reaction.

When considering the model outcome, there is an additional 112 TWh of energy curtailment between the two scenarios.[10] In the model, curtailed energy grows as the share of variable renewables increase in the power market, up to an equivalent to 2,2% of total power generation in 2050.

### Key report highlights

As the CL report outlines, nuclear provides key competitive advantages in future flexible power systems. While variable technologies support the reduction in the carbon intensity of the EU's power systems to a certain extent, only the dispatchable, low-carbon and non-weather-dependant technologies – nuclear – can support the energy system transition under secure conditions (capacity reserve margin).

[9] Joint Research Centre – Foresight 2020.
[10] 172 TWh in the Low scenario and 60 TWh in the High scenario.

# 4. ANALYSIS OF THE RESULTS

## 4.a Medium- and long-term power system results

### Energy mix modelling results

**Share of renewable energy sources vs nuclear based generation.** The low scenario incorporates a vision for 2050 with a limited share of electricity generation from nuclear power capacities (4%), as opposed to the high scenario where nuclear power generation represents 19% of total electricity generation. Under the high scenario nuclear is the second most dominant form of generation after renewable energy sources. The low scenario reflects a higher share of variable renewables (83%) when compared to the high scenario, with a 69% share of variable renewable energy.

While the behavior of the power system in 2050 is not well known, for 2030 there are different reports (i.e. France Strategie [11]) that share concerns about grid instability with more than 40% of power produced by variable RES. This also considers the forecast for deploying flexibility technologies (batteries, H2, etc.). For both of CL's nuclear scenarios, in 2030 variable RES have a generation share of over 40%.

**Thermal capacities and coal phase out:** It was already assumed in the 2018 study that all thermal peaking capacities (Coal and Gas, in particular Open Cycles Gas Turbines - OCGT) are phased out from the market as of 2032.

### Energy capacity modelling results

Considering the transformation in installed power capacities that will occur between 2030 and 2050 throughout the three regions covered, the model forecasts incremental investments in new capacities over the duration of a plant s life, while assuming different load profiles. Under each of the scenarios, flexibility related capacities show the following four characteristics:

1. In order to ensure system security, deployment of large-scale energy storage capacities occurs as of 2040 and operates as a system back up. In 2050, variable renewables sources operate in conjunction with system back up capacities equivalent to 98 GW.[12] The difference between the two scenarios shows that 43 GW of additional battery storage is expected to store variable RES excess power in 2050 and to provide firm reserve capacity. From a system point of view, the need for new storage capacities is emphasized as early as 2030 and gains scale in 2040.
2. On the supply side, the level of the existing capacities (batteries, P2G) which provide flexibility to the system is reinforced under both scenarios, in order to maintain the stability of the system. While in the high scenario the need for installed capacity to provide flexibility is lower than in the low nuclear scenario, it still represents a large absolute amount of 230 GW that is equivalent to 10% of total power system capacity (see section 3.c).
3. Power to X technologies relate to Power to Gas and Power to Heat plants. P2G are integrated as a flexible producer of synthetic fuels via electrolysis that can potentially be used in transportation (e-fuels), the chemical sector (ammonia), or heating (methane).
4. Demand response can be activated during 40 hours per year at 60% of its power. This corresponds to 57 GW.

[11] France Strategie report – January 2021 n°99 n°99.
[12] The reduction of EU nuclear capacities in the Low scenario by 104 GW in 2050 is compensated by a combination of RES capacity to fill in the generation volume gap and flexible capacity to maintain security of supply.

### System adequacy needs

**Implied total system adequacy needs with over 40% variable renewable sources**

The 2021 CL report indicates clear pathways for the replacement of large-scale EU based capacities under the following system security criteria-based cost optimization of:

- Additional T&D infrastructure costs, and
- Network stability costs (ancillary services and grid stability).

The CL report indicates that replacing 100 MW of installed non-intermittent capacity such as nuclear can be executed only if replaced with:

- An available intermittent renewable source with an installed base which is three times larger (i.e. 300 MW of installed capacity), and
- Operating with base load back up capacities of 94 MW.[13]

### System adequacy needs under the high scenario

Over the next decade (2020-2030), the high scenario shows that under security of supply requirements – measured with the need to maintain an EU system adequacy margin – newly installed capacities of nuclear combined with LTOs (132 GW in total) would help to support a large-scale market shifting from fossil fuels. This would avoid power production with a significant, high-carbon content from natural gas (3625 TWh + 1050 TWh incl. UK) and coal (525 TWh).

**Table 2: Phase out scenario benchmark**

| | 2020 | 2025 | 2030 | 2035 |
|---|---|---|---|---|
| France Stratégie with the current phase-out scenarios | 34 | 16 | -7.5 | -10 |
| Compass Lexecon high nuclear scenario (only LTO reference) | 34 | 31 | 21 | 18 |

Source: France Stratégie, Compass Lexecon

### Key report highlights

The report highlights the need for additional capacity operating as back-up:

Flexibility capacities as provided in both scenarios operate so as to ensure total system security needs (see section on flexibility).[14] The comparison between the two scenarios shows that as new additional offshore wind capacities (81 GW) are installed to meet the 2050 decarbonisation objectives, close to 100 GW of flexible capacity will have to operate in order to stabilise both the seasonal and non-seasonal needs of the pan-European system and cope with scarcity situations.

# 4.b Economics

- **Long term power price trends and forecasts**

Modelled electricity prices track fuel commodity prices while reflecting both scarcity situations (with a capacity remuneration) and the progression in carbon prices that indirectly result from the implementation of the Market Stability Reserve mechanism in the carbon market (see the following section).

When it comes to electricity prices, the scenarios presented in the CL report do highlight different market responses.

- Final electricity prices settle at similar levels in 2030 and start an upward trend afterwards in line with the EC carbon price assumptions.
- In the low scenario, nuclear closure and limited nuclear investments do lead to an increase in power prices throughout the modelled horizon.
- In the high scenario, the higher share of nuclear in the power mix is associated with a cost benefit equivalent of €3.5/MWh in power prices for customers compared to the low scenario.

[13]The reduction of EU nuclear capacities in the Low scenario by 104 GW in 2050 would be compensated by a combination of RES capacity and flexibility capacities to maintain security of supply: 369 GW of variable RES capacity + 98 GW of flexibility capacities (53 GW of Power to gas to power; 43 GW of Battery; 2 GW of new (CCS) thermal capacity).
[14]EDF R&D, "Technical and Economic Analysis of the European Electricity System with 60% Renewables", June 2015.

There are two indirect model long-term outcomes:

1. The additional energy cost may affect the competitiveness of electricity versus other energy sources and carriers, which may indirectly affect the decarbonisation of the power sector by slowing down electrification of transport and heating & cooling.
2. With the closure of nuclear capacities, the model brings in additional renewable capacities in interconnected neighboring countries and power prices tend to respond downwards. Such a capacity shift along the supply curve (the merit order effect) as incorporated in the model may ultimately be different according to the regions where the plants are located (reference OECD-NEA).

**Reminder of the EC's Impact Assessment:** Final electricity prices settle at similar levels in 2030 and start an upward trend afterwards. In 2050, the average electricity price in the five different scenario stands at €217/ MWh (in 2015 €) representing a +54% increase compared to the 2015 baseline level.

- **Carbon mitigation costs**

EU carbon prices have been updated in the model in order to incorporate the reform of the EU carbon market mechanism with the revised EU Emissions Trading Directive (EU ETD) covering 2021-2030 (COM 2015/227 Final).

The updated carbon parameters in the 2021 report relative to 2018 are provided below:

- In the 2018 CL report, EU carbon prices were forecast at the level of €25 / tonne in 2025 before rising to €134 / tonne in 2040.
- The 2021 update expects EU-27 carbon prices to stand at €50 / tonne in 2030 rising up to €150 / tonne in 2040. As for the year 2040, the updated report reflects a 12% increase in the carbon price.
- The modelled carbon price in 2030 of €50 / tonne corresponds to the mid-range of the EC's Impact Assessment.

**Reminder of the EC's Impact Assessment:** Across the different scenario and independently of any future expansion of the scope of the ETS beyond 2031, the EU carbon price in 2030 settles in a range that extends between €32 / tonne in 2015 to €65 / tonne.[15]

While the CL report considered the EC's carbon price forecast up to 2050, the market situation has recently evolved. With the carbon price reaching the highest level since its implementation – more than €50 / tonne – the market is already at the 2030 forecast level. The reason for this surge is both the higher EU 2030 climate ambitions and a sustained rising interest from financial investors. With new measures implemented as part of the carbon market reform in June 2021, the carbon price might raise even further, leading to the need to deploy low-carbon dispatchable capacities in order to replace the fossil fuel technologies impacted by the measures – mainly coal, but gas as well.

- **Customer costs**

Customer costs definition: Customer costs build on from non-discounted costs to the end-users of final electricity consumption. They include generation costs (energy and capacity related costs) and carbon related subsidized power plant generation. They exclude grid related charges, levies and taxes.

The anticipated nuclear capacity closures that take place under the low scenario compared to the high scenario directly impact customer costs through:

- Energy cost increases: +€575 billion in additional costs 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 costs:

  -€15 billion from reduced investment in low-carbon baseload generation in the short to medium term;

  -€210 billion from reduced subsidies to low-carbon generation in the short to medium term.

In the run up to 2050, replacing thermal base load generation in combination with lower capacity costs and reduced carbon costs, leads to a more affordable cost for customers with €392 billion in savings (+€25 billion incl. UK).

[15] In the REG and ALLBNK scenario respectively.

## Key report highlights

Overall, an early closure of nuclear plants would increase total undiscounted customer costs by €393 billion over the period 2020-2050, c5% of total customer costs between 2020-2050. Furthermore, 90% of the savings on customer benefits would occur in the short to medium term before 2035.

While this is a strong case for nuclear as it would mitigate costs for consumers when acting as an alternative baseload generation to thermal capacities in the medium term, the case may not be fully valid for future investments in a context where thermal capacities will be able to operate only if fitted with carbon capture and storage (CCS) capacities.

- **Low-carbon technology cost reduction forecasts**

Cost reductions and learning curves for nuclear, wind, solar and batteries are being projected with reference to EU wide consultations on unit investment costs of electricity generation. When designing climate policies, those costs come as policy assumptions to the definition of cost optimal decarbonization pathways.

## Key report highlights

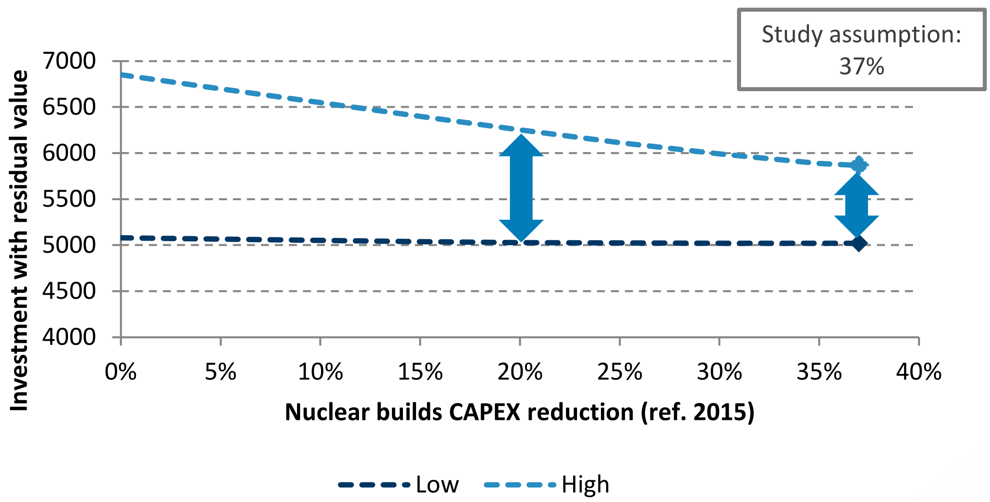
The 2018 study assumed unit investment costs of 4500 USD / kW and learning rates of 63%.[16] While the 2021 study integrated E3M technology cost trends, the investment costs for nuclear remain unchanged with capital cost reductions of 37% in 2020 compared to 2015 in the high scenario.

The aforementioned cost reductions can be achieved through:

- standardized reactor design for First of a Kind (FOAK) projects, cost reduction opportunities, digital materialisation, high-performance concrete, modularity, etc.
- reduction in the cost of finance

**Graph 5: Nuclear new build capex reduction trends**

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




Source: CL 2021 report

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

**Limitations to the CL report:**

- Unit costs and cost composition are intrinsically specific to each technology. Learning from the experience of past projects, the OECD-NEA shows that nuclear investment costs do largely depend on regional circumstances, system integration, market frameworks and, in many instances, financing and project management.[17]
- Technology based learning curves and cost reductions would also need to be put in perspective with the fact that integrating low-carbon technologies imply system-related costs. Recent experience with large electricity production from offshore wind parks constructed through a competitive process (no subsidies) indicate more limited cost reduction potential (see 4.a system adequacy needs).
- For a number of low-carbon technologies, raw material supply dependencies may arise in the future.[18]

### • Residual value of investments

Definition: The residual value is calculated as the sum of capital expenditure (CAPEX) annuities related to operational new investments over their remaining economic lifetime after 2051. The residual value captures the remaining investments to be executed after 2050 for investment decisions that have been taken beforehand and does account for lifetime extension related investments such as LTO. The residual value provides a snapshot view in 2050 that can only be read with the total investment profile in the period 2020-2050.

Modelling results: The total residual value varies according to the total nuclear capacity that will be operating in 2050 in each of the scenarios. In the low scenario (28 GW of capacity in 2050), the residual value stands at €942 billion below the value that comes out in the high scenario (40 GW of capacity in 2050).

Investment profile implication: When looking at the total investment profile, early nuclear closures in the low scenario would save €18 billion in the short to medium term before increasing the total investment costs by €117 billion in the long term.

### • Network and balancing costs

Under the CL model, system costs act as independent parameters to customer related costs. System costs cover transmission and distribution (T&D) network costs and include system balancing costs and tend to be associated to the evolving energy mix needs.

**Modelling results:**

Two long term trends can be mentioned:

- System T&D costs follow the long-term growth in electricity demand.
- System T&D costs evolve in relation to system security and stability needs, notably long-term balancing needs. As more RES operate in the low scenario (and over time in both scenarios), this requires more balancing capacities in the low scenario in comparison to the high scenario (and in both scenarios over time).

The estimation of T&D system costs is derived from a review of the academic literature.

### Key report highlights

Compared to early nuclear closures under the low scenario, further nuclear development in the high scenario would reduce network and balancing costs by €168 billion (real 2019) by 2050. This accounts for 17% of the total T&D grid costs cumulatively over the 2020-2050 horizon, of which €26 billion comes from offshore grid cost and €10 billion results from additional balancing costs.

dependence on fossil fuels to an equivalent of +26% in gas consumption and +12% in coal consumption between 2020 and 2050.

[17]OECD-NEA, Unlocking Cost Reductions in the Construction Costs of Nuclear: A Practical Guide for Stakeholders, 2021.
[18]Joint Research Centre, Raw materials Foresight 2020 Study.

# 4.c Security of supply

**Modelling results:**

The difference between the high scenario and the low scenario helps to understand the security related benefits of nuclear energy.

- A low share of nuclear in the energy mix will significantly increase the power system's reliance on large scale yet immature storage technologies (reaching around 325 GW of batteries and seasonal storage such as Power to Power in 2050 in the Low scenario).
- By closing nuclear capacity instead of investing in its long-term operation, 2370 TWh of additional fossil fuel based thermal generation will be needed in the short to medium term, representing a +22% increase or the equivalent of 4 years of the EU's total power generation.
- The low nuclear scenario would increase fossil fuel consumption (gas and coal) by 4150TWh, pushing up Europe's dependence on fossil fuels to an equivalent of +26% in gas consumption and +12% in coal consumption between 2020 and 2050.

**Key report highlights**

With nuclear as part of the energy mix, the energy system shows less reliance on non-mature storage technologies. Meanwhile, the absence of nuclear increases the reliance on thermal based generation and dependency on imported fuels.

# 4.d Hydrogen production

Hydrogen is used in the energy value chain as a primary energy input or fuel and contributes to the final energy consumption from both the mobility and the industrial sectors (e.g. the chemical sector). In the electricity system, hydrogen can be used to generate power during hours where a marginal cost difference opportunity arises, at times when its marginal generation cost stands below other variable renewables.

**2021 model updates:**

The CL 2021 report update incorporates hydrogen production for use in industry.

- Via the electrolysis process, hydrogen can be produced for industry from two feedstocks (electricity and water).

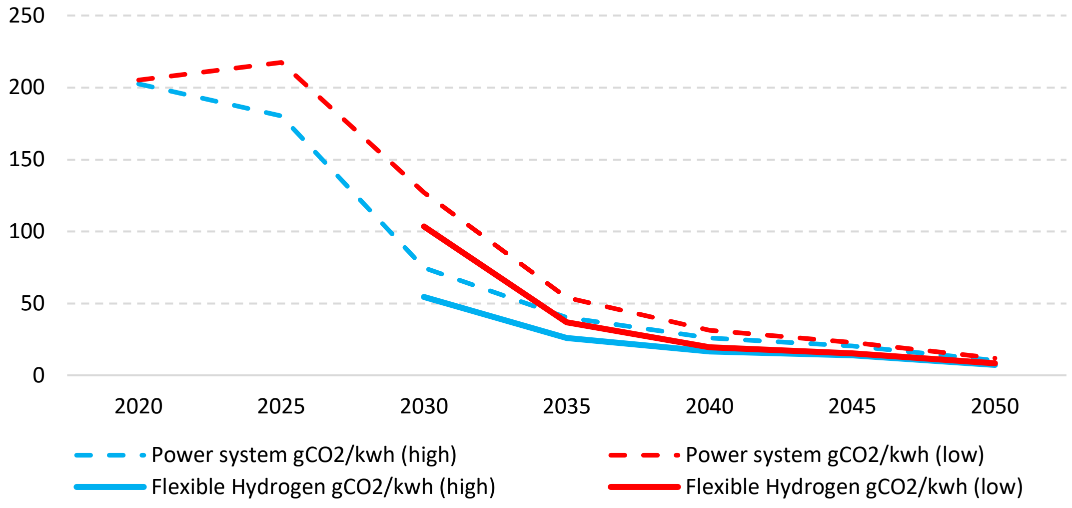
The CL model runs an optimized power consumption where hydrogen is produced at times of low marginal electricity costs based upon load reduction factors.[19] Overall, in the 2021 update and on a daily basis, hydrogen ($H_2$) contributes to a fluctuating load of between 0 TWh and 2 TWh.[20] As hydrogen and hydrogen-based fuels require additional power demand (with an average electrolyser efficiency of 75%), the power demand curve for 2050 has also been adjusted upwards (see 3-a).

[19] 50% of industrial hydrogen production can be reduced 500 hours per year at 60% of its power while the rest can be stopped.
[20] International Atomic Energy Agency (2013), Hydrogen Production Using Nuclear Energy, Nuclear Energy Series No. NP-T-4.2, Vienna: IAEA.

**Modelling results:**

- Hydrogen production helps to reduce average CO2 intensity up until 2040. After 2040, the carbon intensity (in g/KWh) benefit from hydrogen production is more limited, as hydrogen's relative marginal costs lose their competitive advantage in power systems with high variable renewables.
- In 2050, with the decarbonisation of the power system, 82% of hydrogen production would come from renewable based capacities and 18% from nuclear under the high scenario.
- During some hours, hydrogen can help to provide an additional benefit in terms of flexibility while contributing to security of supply. During those hours, equivalent flexibility reserves of between 28 GW and 60 GW can be activated when necessary.

### Graph 6: Carbon content of power by scenario (gCO2/kwh) – Hydrogen and system comparison




Source: CL 2021 report

## Key report highlights

In order to pay back the high capital investment (Capex) of the electrolysers, capacity factors need to stay within a range of 3000h – 6000h. Matching the electrolyser load factors with variable renewable electricity production profiles can be done only under precise circumstances as illustrated in the FORATOM background paper on Nuclear Hydrogen Production – A key low-carbon technology for a decarbonised Europe.

# 4.e Impact on environment and resources

The following section focuses on environmental sustainability and therefore looks at the various environmental impacts of nuclear energy, including resource consumption.

- **CO2 emissions**

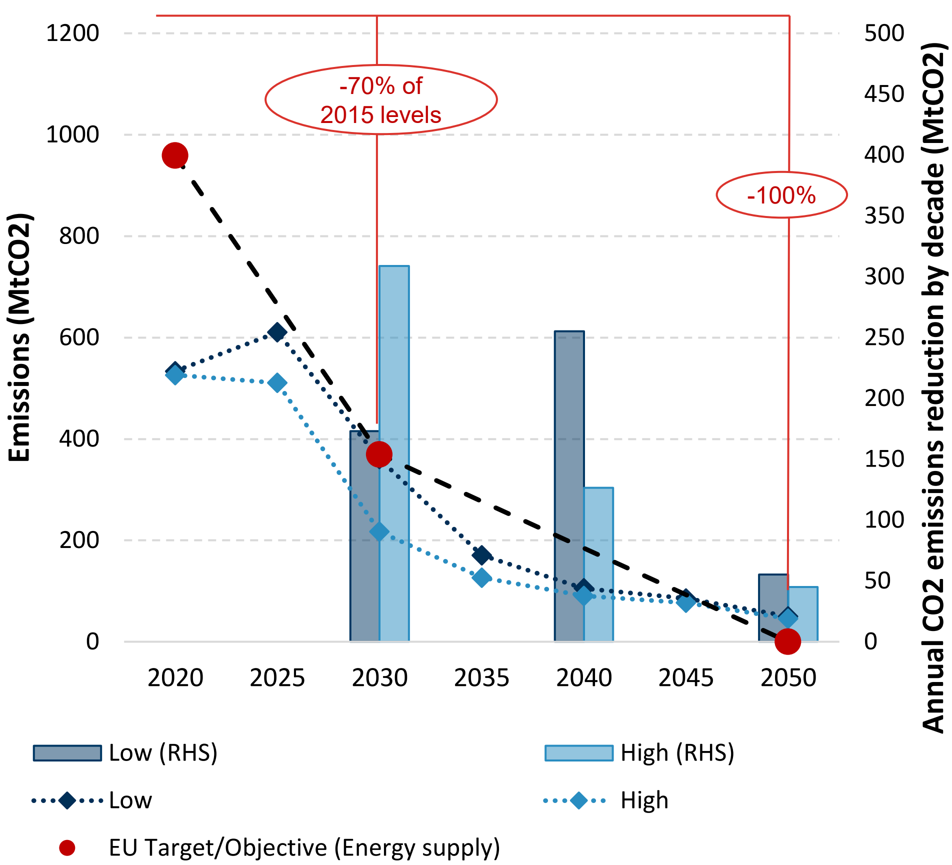
In terms of climate mitigation targets, the CL 2021 report considers that the 2030 and 2050 CO2 power sector reduction goals are achieved in both nuclear scenarios.

- In 2030, the CL low and high nuclear scenario foresee a reduction of 400 Mt CO2 and 600 Mt of CO2 emissions (respectively) in the power sector;
- In 2050, the CL low and high nuclear scenario foresee a reduction of 300 Mt CO2 and 250 Mt of CO2 emissions (respectively) in the power sector.

While in the EC Impact Assessment other greenhouse gas (GHG) abatement sources (methane, SOx, NOx) do contribute to the 2050 climate mitigation objectives, the CL model and study focus on GHG emissions from power generation activities.

The CL study also notes that the anticipated closure of nuclear power plants under the low scenario would lead to increased CO2 emissions by 2025, thus potentially jeopardizing the increased 2030 climate mitigation ambition.

**Graph 7: Power sector CO2 emissions outlook 2020-2050 - High and Low scenario**




Source: CL 2021 report

- **Raw material usage**

**Modelling approach and potential ways of capturing raw material usage**

As discussed in previous sections, the CL power generation model mainly operates under a market-based optimization of the energy produced by all EU-27 + UK based power generation units up until 2050. It also covers the relevant long-term air pollution and land use related impacts of power generation (see section on land use). In addition, the CL model can be used to help assess wider sustainability dimensions linked to other activities, such as the resource intensity of each energy source. To this extent, the following additional indicators are being looked into:

- Energy intensity indicator: At the level of an energy system, the energy intensity equals the primary energy consumed divided by the energy produced. Energy intensity is an energy flow-based indicator acting as a major driver of a system carbon intensity.
- Resource intensity indicator (in materials grammes / GWh or in kg / MW) can also help identify the volume of raw materials required to produce specific amount of energy underpinning the CL 2021 model outcomes.

**Resource intensity of non-fossil natural sources**

In a similar approach to energy intensity, the resource intensity of a specific power generation technology can be used to assess the raw material footprint of the energy produced. This report focuses on non-fossil natural sources via a selection of key raw material and mineral resources.

In nuclear power generation, a differentiation can be made between the materials that fall into structural elements or components of a power plant and non-structural materials and metals. The structural materials relate for instance to concrete, steel, aluminum, copper or chrome. The non-structural elements are metals and raw materials such as nickel, chromium or molybdenum used as steel alloys. Some elements can fall into two categories (e.g. aluminum and copper can be used in structural elements but also components).

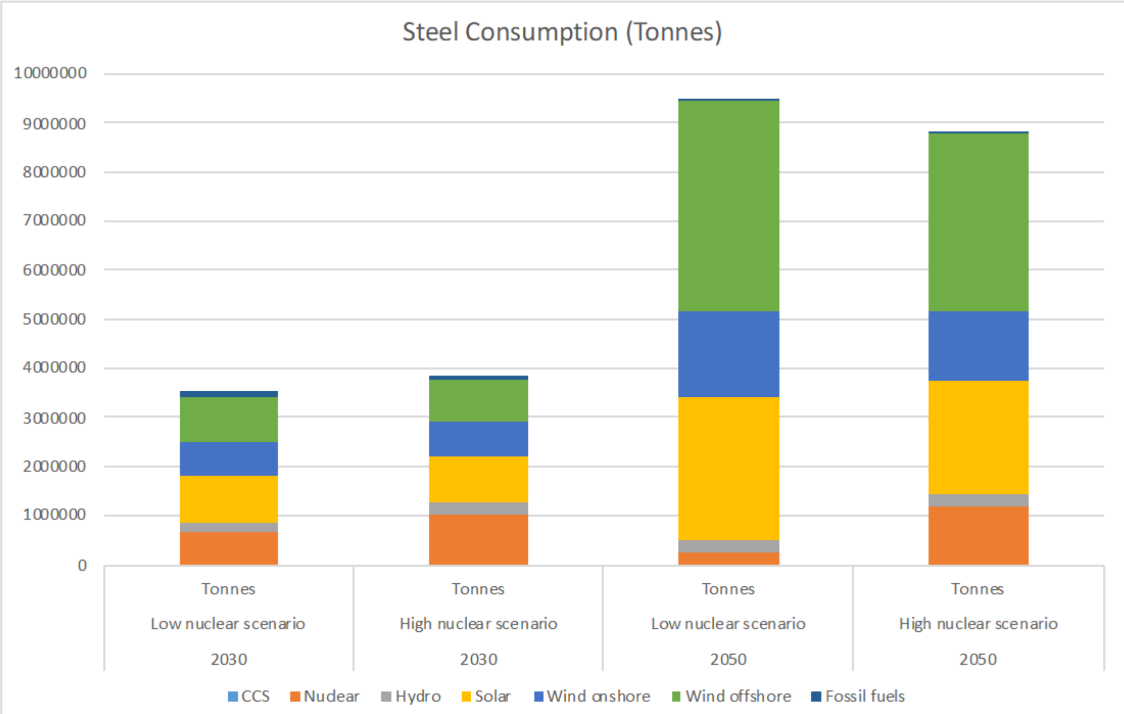
**Resource's assessment case example**

Resource use assessment methodology: The LCA standard approach is the most established methodology when it comes to evaluating environmental impacts over the lifecycle of a technology and a defined scope of activities.[21] Based upon the LCA methodology, FORATOM has calculated the amount of raw materials that would be required according to the power generation operating in 2030 and 2050 under the high and low scenario. This amount is provided as an absolute volume level.

Two examples are given below: steel and concrete. In terms of raw material usage, the main components of these construction materials are limestone and aggregates (concrete) and iron ore and steel alloys (used in steel). Steel alloys include a variety of metals such as chromium that is utilised in high performance steel alloys.

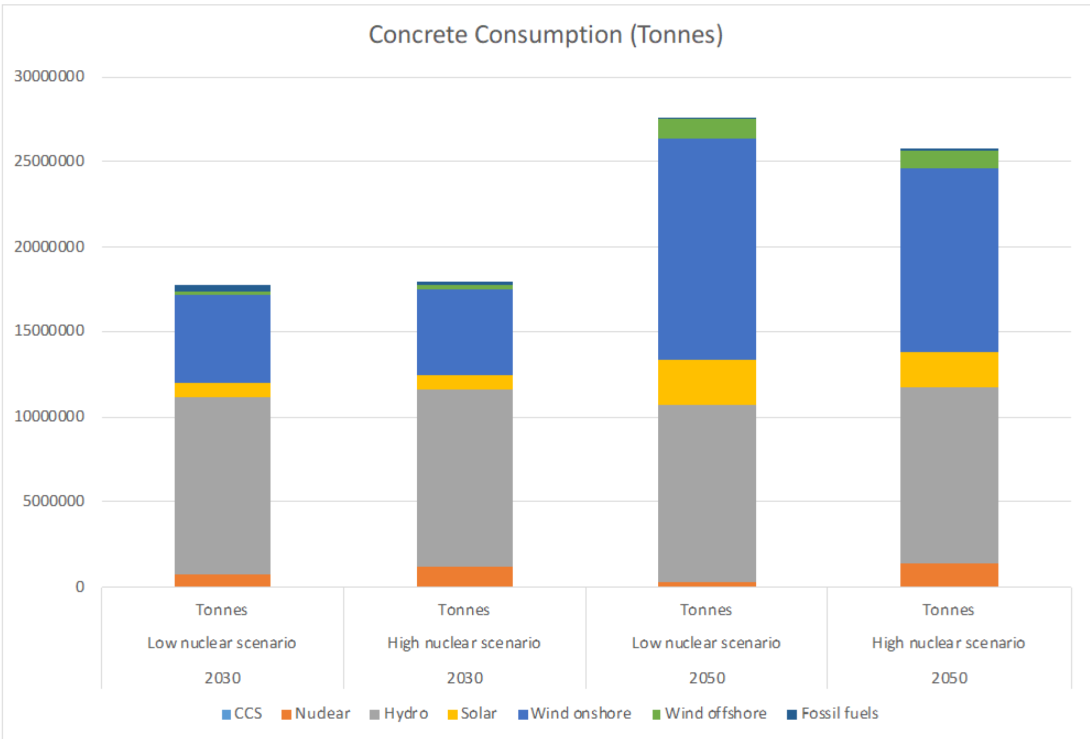
[21]Nuss, P., and M. J. Eckelman. Life Cycle Assessment of Minerals: A Scientific Synthesis", 2014; EDF EROEI concept, EDF Research and Development, Jean-Michel Trochet, 2020.

## Graph 8: Steel related LCA based assessment of power generation



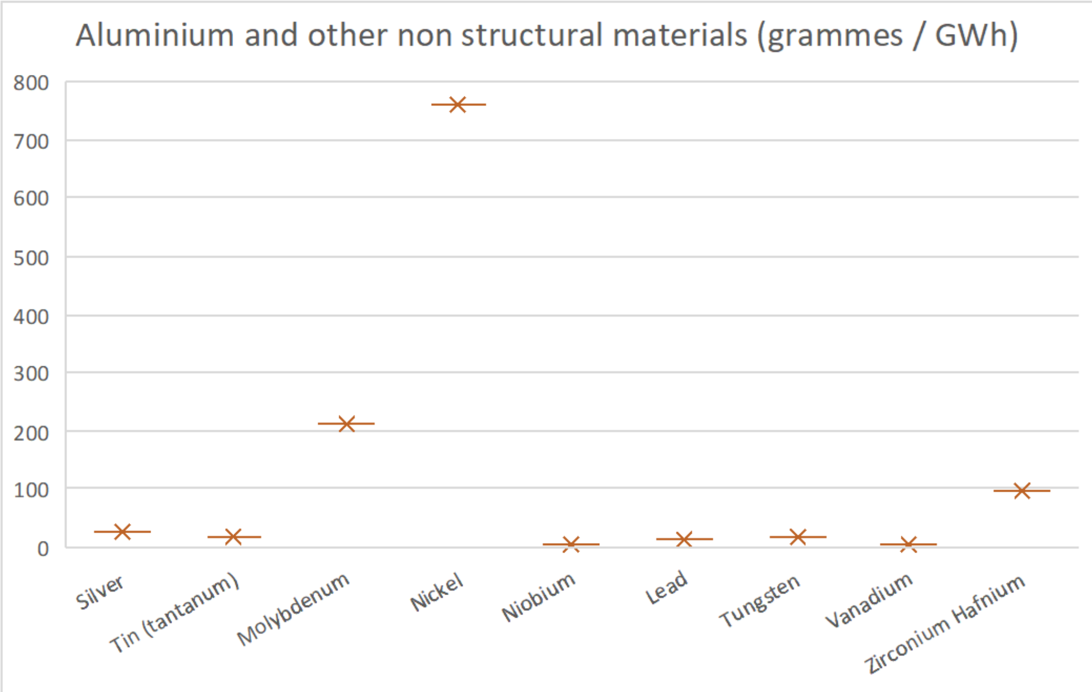

Source: EDF R&D calculation (2020)

## Graph 9: Concrete related LCA based assessment of power generation




Source: EDF R&D calculation (2020)

**Graph 10: Overview of other metals and materials**




Source: EDF R&D calculation (2020)

As part of the energy transition, low-carbon energy technologies need to be deployed on a large-scale level as indicated by the amounts of GW necessary by 2050. While newly installed capacity does imply a significant increase in the demand for non-fossil raw materials, nuclear compares well with other low-carbon technologies as most of its materials (with the exception of borates) can be sourced from locations where they are abundantly available (see references to the International Energy Agency).[22]

- **Other air pollution SO2, NOx and PM**

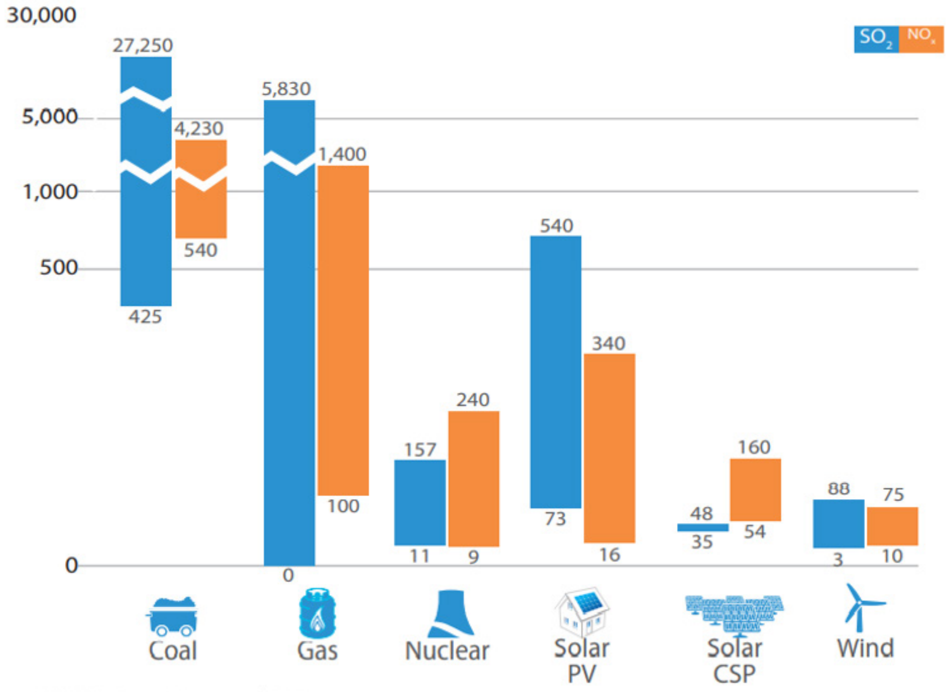
Reducing CO2 emissions is key to tackling climate change, but it also important to take into account other emissions and pollutants, which have a negative impact on human health, such as sulphur dioxide (SO2), nitrogen oxides (NOx), and particulate matter (PM). Estimates by the World Health Organisation indicate that every year three million deaths globally are caused by ambient air pollution and by particulate matter released mainly through the burning of coal or biomass.[23]

**Carbon based sources:** According to the International Energy Agency (IEA), the power sector is responsible for one-third of SO2 emissions, which causes acid rain, 14% of NOx emissions, a precursor pollutant for particulate matter (PM) and ground-level ozone, and 5% of particulate matter (PM2.5). Those emissions mainly derive from fossil-fuel sources (coal, natural gas, oil and biomass) that do emit local air pollutants during electricity generation.

[22]World Energy Outlook Special Report, The Role of Critical Minerals in Clean Energy Transitions International Energy Agency, May 2021.
[23]World Health Organizatio, Ambiant air pollution: a global assessment of exposure and burden of disease, 2016.

**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 power plant construction.

### Graph 11: Lifecycle $SO_2$ and $NO_x$ emissions by different generation technologies (mg/kWh)




Source: FORATOM

This point is further confirmed by the JRC's environmental standards for the supply of electricity and heat. Drawing from life cycle scientific assessments, the JRC shows that nuclear, wind and hydro have relatively very low NOx and SO2 emissions when compared to coal, natural gas, biomass and solar PV.

### Key report highlights

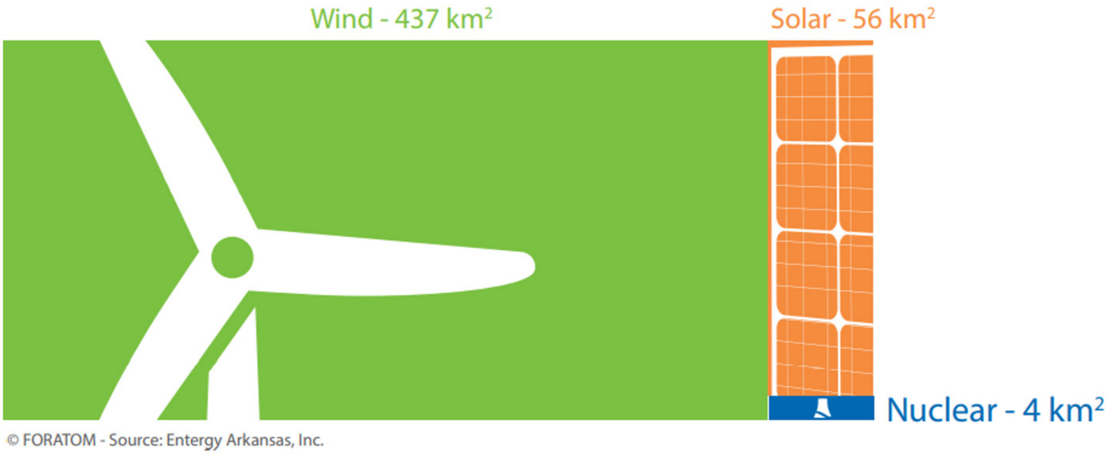
Based on the low nuclear scenario, CL concludes that an early closure of nuclear plants would require new thermal capacities in order to ensure security of supply, as well as additional thermal generation from existing plants. This would lead to an increase in air pollutants as follows:

- SO2: 2.4Mt of additional SO2 emissions or 7.7% of total SO2 emissions over 2020-2050
- NOx: 1.6Mt of additional NOx emissions or 7% of total NOx emissions over 2020-2050
- PM: 1650kt of additional PM emissions or 12% of total PM emissions over 2020-2050

- **Land use and impacts on biodiversity**

Land use is an important issue as the larger the land footprint of a technology, the greater its potential environmental and biodiversity impacts (eg loss of flora and fauna).

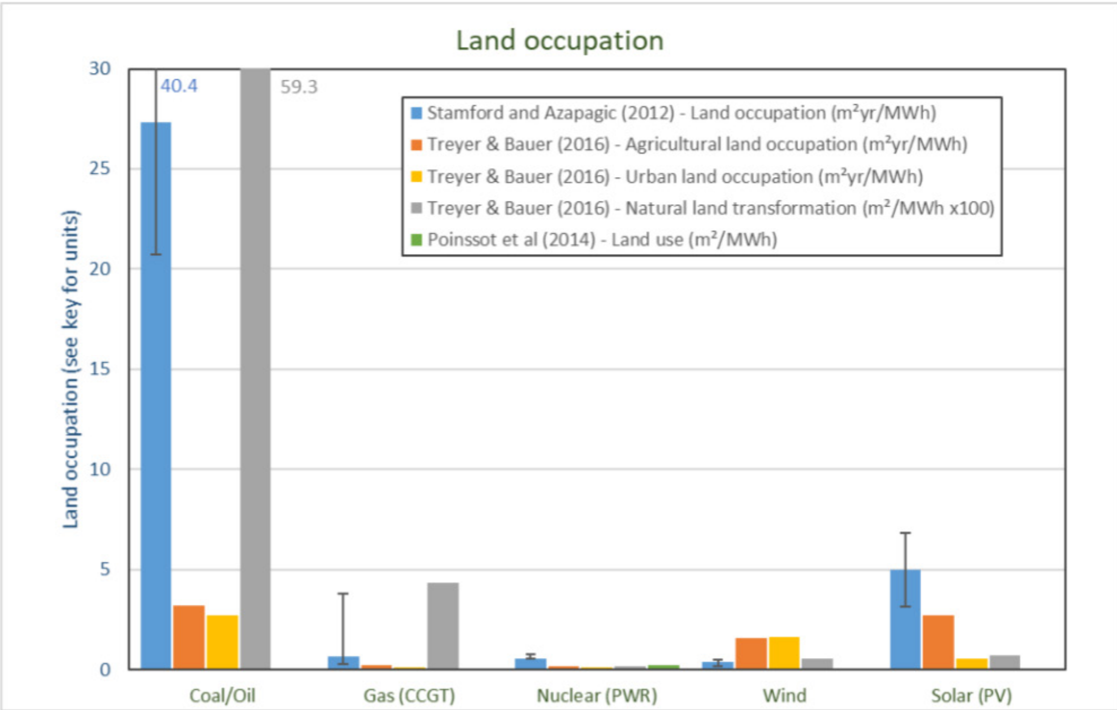
### Graph 12: Land use assessment - Equivalent 1800 MW low-carbon technologies (km2)




Source: FORATOM

According to the CL report, nuclear has one of the lowest land use footprints of all electricity producing technologies based on a full life cycle assessment (140 m2/GWh).[24] This point is further confirmed by the Joint Research Centre in its recent analysis of nuclear under the Sustainable Finance Taxonomy, as illustrated below.

### Graph 13: Life cycle assessment and land occupation



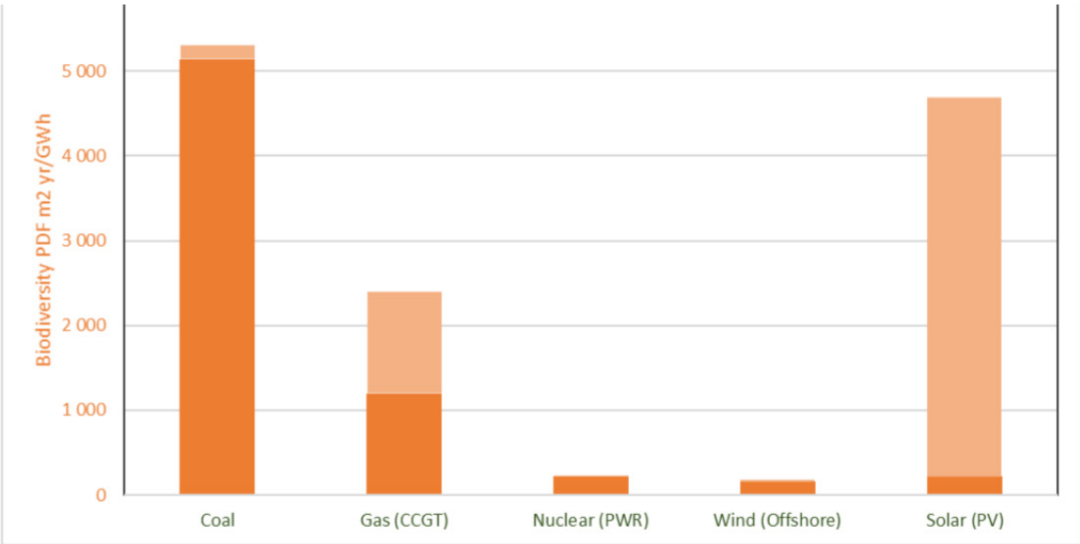

Source: Joint Research Centre

[24]Fthenakis et Al, 2019.

**Limitations to the CL report:** Other biodiversity impacts

Modelling of land use falls outside the scope of the CL report, however the JRC report does delve into more detail on how the land use impacts of the different technologies can affect biodiversity. Here again, the data shows that nuclear compares favourably to other technologies:

### Graph 14 : Biodiversity Impacts




Source: Joint Research Centre

As such, it can be concluded that a higher share of nuclear in the energy mix reduces pressure on land and biodiversity.

## Report highlights

The land use assessed in terms of the number of hectares needed to produce a specific volume of electricity from nuclear power plants is massively lower than, for example, wind farms. Not only does this reduce the visual impact of energy generation, but it also limits land use change and the loss of biodiversity and natural habitats.

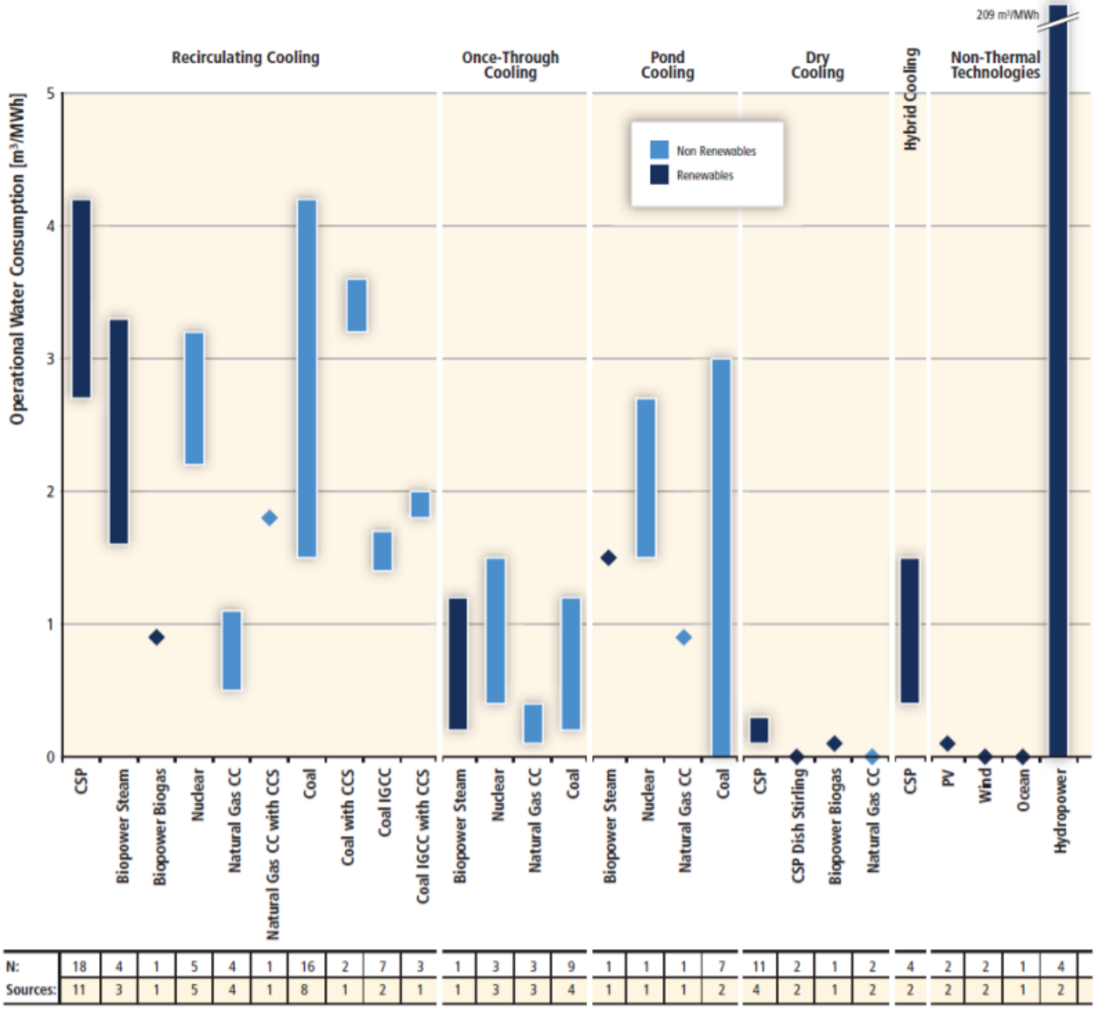
Based on the assessment conducted by CL, an early closure of nuclear plants (under the low scenario) would require new solar and wind capacities in order to meet decarbonisation objectives, which would generate an estimate derived from the literature of 9890 km2 of additional land requirement or 7% of total land use over 2020-2050.

- **Impacts on water**

As highlighted by the JRC report, thermal technologies, such as nuclear energy, have relatively high water consumption requirements when compared to non-thermal renewable technologies. In the case of nuclear, the vast majority of water is consumed as cooling water during the operation of the power plant, although volumes can vary depending on the cooling technology used. Graph 14 shows the range of operational water consumption per technology, and notes that whilst nuclear consumes more water than solar PV, wind and ocean energy, it is comparable – or even better than – concentrated solar, hydropower and biomass.

## Graph 15: Operational water consumption in power generation

**Figure 3.2-7**[28]. Ranges of rates of operational water consumption by thermal and non-thermal electricity-generating technologies ($m^3$/MWh)[29]




Source: Joint Research Centre

Another important aspect to take into account is the potential thermal pollution (increase in water temperatures) when the heated-up cooling water is returned to the water body.

According to the JRC, the potential impacts of nuclear energy on water consumption and thermal pollution of water bodies must be appropriately addressed during the site selection, facility design and plant operation phases.

# 5. CONCLUSIONS

The report highlights the needs for additional flexibility capacities operating as back-ups in the future low-carbon systems. The comparison between the two CL scenarios (high and low scenario) shows that as new additional offshore wind capacities (81 GW) will be required to meet the 2050 decarbonisation objectives (climate neutrality in 2050), while close to 100 GW of flexibility capacities will have to operate to stabilise both the seasonal and non-seasonal needs of the pan European system and cope with scarcity situations.

Nuclear does provide a key competitive advantage in future flexible power systems. While flexible technologies support the reduction in the carbon intensity of EU's power systems to a certain extent, the only dispatchable, low-carbon and non-weather dependent technology which can support the energy system transition under secure conditions is nuclear.

Overall, the early closure of nuclear plants would increase the total undiscounted customer cost by €393 billion between 2020-2050, or 5% of total customer cost over 2020-2050. Compared to early nuclear closures under the low scenario, further nuclear developments underthe high scenario would reduce network and balancing costs by €168 billion (in real terms 2019) by 2050.

90% of the savings on customer benefits would occur in the short to medium term before 2035. While this is a strong case for nuclear in providing cost mitigation to customers when acting as an alternative baseload generation to thermal capacities in the medium term, the case may not be fully valid in a context where thermal capacities would be able to operate with carbon capture and storage (CCS) capacities. The growth of hydrogen as an energy carrier in future systems will also have implications for both energy demand and system operations.

| Sustainability impacts | Main Highlights Compass of the Lexecon 2021 Report |
|---|---|
| Greenhouse gases emissions - Carbon emissions | Early closure of nuclear under the low scenario would lead to increased CO2 emissions by 2025, thus hampering the increased 2030 climate mitigation ambition |
| Greenhouse gases emissions - Other air pollutants (SO2, NOx, PM) | Based on the low nuclear scenario, an early closure of nuclear plants requires new thermal capacities in order to ensure security of supply. This would lead to an increase in air pollutants as follows:<br>▸ SO2: 7.7% increase in total SO2 emissions over 2020-2050<br>▸ NOx: 7% increase in NOx emissions over 2020-2050<br>▸ Particulate Matter (PM): 12% increase in total PM emissions over 2020-2050 |
| Raw material usage | A comparative example is provided with concrete and steel materials. Among all large-scale low-carbon energy technologies, nuclear based deployment pathways show the lowest materials intensity as reflected by the volumes of materials necessary by 2050. Most of the raw materials used in the nuclear value chain are abundantly available. |
| Land use impacts | An early closure of nuclear plants (under the low scenario) would require new solar and wind capacities in order to meet environmental objectives, which would generate an estimate derived from the literature of 9890 km2 of additional land requirements or 7% of total land use between 2020-2050. |
| Water related impacts | Not included in the CL report scope, nor in the conclusions taken from the CL report. |

**Water related impacts:**

Water impact assessments can be conducted in addition to land use impact assessments. Whilst nuclear consumes more water than solar PV, wind and ocean energy, it is comparable with – or even better than – concentrated solar, hydropower and biomass.

# 6. POLICY RECOMMENDATIONS

In order to achieve carbon neutrality by 2050, the European Union has committed to increase its climate ambition by 2030 to at least a 55% net reduction in greenhouse gas emissions compared to 1990. This ambitious climate neutrality goal will entail an unprecedented transformation of the power sector by switching from emitting fuels to low-carbon technologies. Supported by the current EU's policies, a massive penetration of renewables sources will occur, and it will be backed up with the deployment of energy storage and low-carbon hydrogen, as an energy vector.

Drawing from the findings presented earlier in this report (see sections 4. and 5.), the policy recommendation section presents six policy takeaways that illustrate how nuclear energy will play an essential role in supporting the EU's ambition of becoming climate neutral in 2050.

This section focuses on four policies: 1. The EU's decarbonization policy; 2. Energy security policy; 3. The EU's hydrogen Strategy; and 4. The EU's energy market design.

## 6.a EU's decarbonisation policy

Within the perspective of strengthened EU's climate objectives under the European Green Deal and the Fit for 55 package, three policy takeaways are being proposed.

**Policy takeaway 1: Nuclear energy is an affordable solution for achieving the EU's climate ambition.**

When looking forward to 2050, all modelling scenarios indicate that the EU's electricity system will operate with high shares of variable renewables. The CL model envisions a 79% share of variable renewables in 2050 under its high nuclear scenario.

*Nuclear helps achieve the required levels of system flexibility at the lowest cost (see 4. Analysis of the results).*

- Nuclear does not only operate as a base load energy source, but is also able to operate under a load following mode. [25] Therefore, nuclear **provides flexible capacity as required in power systems where a high share of variable renewables also operate.**
- Over time, as **new technologies** such as **energy storage or hydrogen see their share progressing in the energy mix** (and depending on the future of carbon capture and storage technologies (CCS)), the CL report shows that **the high nuclear scenario is the most affordable scenario.**

**Nuclear provides affordable energy to final consumers.**

Assuming that unit investment costs stay on track in accordance with the CL forecasts to 2050 and under the high scenario, the energy system can be decarbonised at an affordable cost in 2050. In fact, nuclear contributes to an affordable energy system, thereby mitigating final energy consumer costs.

**Policy takeaway 2: The early closure of nuclear power plants risks derailing long term decarbonisation goals.**

The early closure of nuclear power plants will entail a range of different effects. On the one hand, their substitution by thermal power plants will impact the EU's planned CO2 emission reduction pathway by leading to an increased in greenhouse gas (GHG) emissions by 2025 (see 4.b Economics). Depending on the CO2 price under the EU Emissions Trading Scheme (Directive 2003/87 EC), this would also lead to an increase in final electricity costs.

On the other hand, the early closure of nuclear power will also trigger environmental impacts such as greater land use, as well as higher raw material and water consumption mainly due to the need to deploy more renewables. Furthermore, the early decommissioning of one of Europe's largest sources of dispatchable low-carbon energy source could have a significant negative impact on the electricity adequacy level (see Policy takeaway 4).

[25] Under a load following mode, some of France's nuclear power park plants ramp up or down between 100% and 20% of their nominal power in half an hour, and after at least two hours, twice a day.

**Policy takeaway 3: To ensure a sustainable transition, all low-carbon technologies must be subject to the same robust and scientific assessment.**

Under the EU Green Deal (COM(2019) 640 final), scientific evidence is needed to demonstrate how different energy sources and technologies, and their integration at the energy system level, can help the EU to achieve its net-zero objective in 2050. Such evidence should meet the principle of technology neutrality and include references to internationally recognized sustainability metrics.

The CL report provides insights into the Life Cycle Assessment methodology (see section 4.e), an internationally recognized metric for environmental impact assessments. This methodology can also be found in a recent report from the Joint Research Centre, that shows that nuclear energy has a relatively low environmental impact when compared to alternative low-carbon sources of energy.[26]

# 6.b Energy security policy

Under the EU Green Deal, decarbonisation policies must be accompanied by a framework guaranteeing security supply.

**Policy takeaway 4: Nuclear is a low-carbon technology which ensures security of supply.**

With an asset life of 60 years or more, combined with reliable uranium supplies for nuclear fuel fabrication, nuclear energy ensures long term security of supply in the different regions where it operates. It also alleviates Europe's dependence on fossil fuel imports (see FORATOM Security of Supply Position Paper - 2015).

From an operational reliability and resilience point of view, recent events show that a higher share of variable RES (above 40%) could put the electricity grid at risk of instability and interruptions. See, for example, the medium-term adequacy analysis made by the system operator RTE in relation to harsh winters (RTE 2019).[27]

Therefore, the role of nuclear in contributing to security of supply shall also be emphasized in future security related policies.

The CL energy modelling incorporates ENTSO's adequacy assessment and shows that forecasted nuclear power capacities in 2050 (132 GW in the high nuclear scenario) will help to ensure security of supply in the EU. The conclusions are in line with the International Energy Agency recently proposed security framework.[28-29] Compass Lexecon's high nuclear scenario shows that the dispatchable profile of nuclear can be associated with comparatively lower balancing requirements in low-carbon systems. Today, the most modern nuclear power plants (Gen III reactors) operate with an annual capacity factor of over 90% on average.

# 6.c EU's energy market design

**Policy takeaway 5: A market design in support of all low-carbon technologies.**

Under the EU Green Deal, a market design for low-carbon energy technologies may encourage investments in nuclear and other low-carbon technologies. As highlighted by the CL report, some technologies (energy storage and hydrogen) have yet to demonstrate that they can be rolled out at scale and at affordable cost.

The need for regulated asset frameworks and hybrid market designs can be further explored. Such frameworks may in the future incorporate capacity remuneration approaches while taking into consideration risk mitigation instruments (see FORATOM Investment Framework Task Force report - 2021).

[26] Joint Research Centre, Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation'), 2021.
[27] RTE, Electricity Report, 2019.
[28] When considering seasonal and non-seasonal flexibility needs and the weather dependent nature of renewables-based intermittency.
[29] Within a pan European or a regional integrated electricity market, adequacy assessments do provide a view on whether an integrated system can cope with unplanned events and flexibility needs and under what forms (back-up capacities, capacity reserves, grid reserves) and horizon (see the national TSOs and the ENTSOe mid-term or long-term adequacy assessments).

# 6.d EU hydrogen Strategy

**Policy Takeway 6: Nuclear supports a sustainable hydrogen economy.**

The EU Hydrogen Strategy adopted in 2020 mainly supports the so called renewable or clean hydrogen, produced using renewable power. The strategy also mentions a low-carbon hydrogen category (fossil plus CCS or produced from low-carbon power) that is seen as a transitional solution. In FORATOM's opinion, which is confirmed by the CL report, a sustainable hydrogen economy cannot exist without including nuclear power as an important source (see FORATOM Hydrogen Position Paper - 2021).

## Annex1: Energy Return on Energy Investment (EROEI) definition

A study published study on EROEI, by Weissbach et al (2013), provides the definition of EROEI. The EROEI of a "power plant is the ratio of the usable energy that the plant returns during its lifetime to all the invested energy across its lifecycle divided by the amount of energy needed to make this energy usable".[30] The EROEI can be considered as directly correlated to the energy intensity and independent from capital investment related costs. In the Weißbach et al. (2013) study, and as reflected in the graph below, the EROEI for nuclear stands above 30 and up to a level of 75, the highest level when compared to other power generation technologies. In the specific case of nuclear, it is worth noting that the EROEI increases with the extension of the lifetime. In an EROEI analysis, nuclear features closer to hydro generation that come second in the ranking of EROEI at close to 30.

### Graph 13: EROEI ranges for low-carbon technologies

| Low carbon technologies | EROEI scale indicators |
|---|---|
| Solar PV | < 10 |
| Wind offshore or onshore | < 15 |
| Large hydro | > 30 |
| Nuclear | > 30 |

Source: EDF Research and Development, Weißbach et al. (2013)

## Annex 2: EC Long-Term Strategy Scenario

The EC's Long-Term Strategy analyses different pathways in support of the Paris agreement target of keeping the temperature increase since the pre-industrial era "well below 2°C by 2100".

There are five main pathways of the Paris Agreement reflecting different technological choices on how to decarbonise the EU economy:

- Energy efficiency (EE): Pursuing deep energy efficiency in all sectors, with higher rates of building renovation.
- Circular economy (CIRC): Increased resource and material efficiency, with lower demand for industry thanks to a higher recycling rate and circular measures.
- Electrification (ELEC): deep electrification of all sectors, with large deployment of heat pumps for building heating and faster electrification of all transport modes.
- Hydrogen (H2): Hydrogen is used in all sectors and injected into the distribution grids to be used in buildinsg for heating, and for freight transport.
- Power-to-X (P2X): Large development of e-gas and e-fuels to decarbonise the different vectors without changing the energy supply type

[30] Weissbach_EROI_preprint.pdf (festkoerper-kernphysik.de).

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