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EUCALC

Explore sustainable European futures

WP5 – Energy supply module documentation

Deliverable 5.1

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Short Description
This report introduces the energy supply module of EUCalc by describing the trends, setting the scene and providing the basis for the methodology of the calculation. Having reviewed the background, the report then goes on describing the ambitions and goals of this specific module. After this, it describes the overall calculation logic of the module, detailing the input, outputs, the module's relation to other modules and the detailed calculation tree. The calculation methods are thoroughly explained, by detailing the scope, the choice of the lever levels, and the influence of a multitude of external factors.

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List of abbreviations

CCS – Carbon Capture and Storage

CHP – Combined Heat and Power

CSP – Concentrated Soler Power

DSM – Demand Side Measures

EUCalc – European Calculator project or model

EV – Electric Vehicles

GHG – Greenhouse Gas

LCOE – Levelized Cost of Electricity

NREAP – National Renewable Energy Action Plan

PV – Photovoltaic

VRE – Variable Renewable Electricity

1 Introduction

Decarbonization of the electricity generation sector is an important factor in reaching the climate targets of the EU. The emissions by the public electricity and heat production is the largest key category in the EU-28 and Iceland accounting for 24% of total GHG emissions in 2016. Nevertheless, the sector is already on a path of greenhouse gas (GHG) emission reduction due to the growing share of renewables and shrinking fossil fuel-based capacities. These trends are expected to continue in the future as renewables become more competitive while coal power plants more obsolete.

The module and the levers within aim to show the impact of different scales of penetration of renewable based technologies, phase-out schedule of coal power plants and the different positions on nuclear energy influence the long-term, economy-wide GHG reduction objective which is a fully decarbonised power generation sector in Europe. Currently, the main source of emission (accounting for 51% on EU level) is the coal based power plants, thus phasing out them and substituting them by renewables or even natural gas can lead to mitigation of the emissions. These measures are in the scope of the electricity generation modelling within the energy supply module.

The objective of this report is to provide a structured, documented and transparent view of the GHG emission pathways in the electricity supply sector in European Union and Switzerland until 2050. This report identifies and details the various levers that influence GHG emissions from the electricity generation. For each lever, extensive documentation is provided to describe the various ambition levels ranging from a low ambition level to a disruptive ambition level. Ambition levels are proposed based on most up to date research, historic trends and other relevant work and studies.

Not only for the electricity generation, but for the oil refinery sector and hydrogen production sub-modules, the calculation methods are thoroughly explained by detailing the scope, the choice of the levers, the influence of a multitude of external factors and the calculation method.

2 Policy recommendations

Decarbonization of the electricity generation sector is an important factor in reaching the EU climate targets. The sector is already on a path of greenhouse gas emission reduction due to the growing share of renewables and shrinking fossil fuel-based capacities. These trends are expected to continue in the future as renewables become more competitive while coal power plants more obsolete.

Emissions from electricity production scenarios simulated in the EUCalc result from the amount of electricity needed (depending on demand side actions, not detailed here, given that they are modelled in other modules of the calculator) and the mix of technologies required to generate that amount of electricity. The latter is subject of policy debates and different targets, and as such the levers represent different ambition trajectories for different power generation technologies.

The solution for decarbonisation of electricity production is focused on three main strategies: the phase-out of high emission technologies; the mainstreaming of renewables and the role of nuclear power. The phase-out process is driven by economic necessity (due to ageing of plants) or by policies. Regardless of policies, coal-based power generation is forecasted to decrease; however, policies can speed up the phase-out process, contributing to timely decarbonisation efforts.

Regarding nuclear power, its role divides opinions. Whilst some EU Member States aim to phase it out as soon as possible, others want to maintain it and consider it as an instrument for decarbonisation. The impacts of different nuclear policies and their timing are also an important aspect of developing decarbonisation policies. However, our analysis shows that even with a highly ambitious policy to maintain nuclear, its total capacities still tend to decrease over time, thus reducing its role in decarbonising the electricity sector.

Unlike nuclear power, EU Member States unanimously look at renewables for decarbonizing their electricity mix. Nevertheless, the historical experience, current situation and, more importantly, the renewable electricity potential that can be locally exploited in the coming decades vary among Member States. The recent growing share of renewables has been led by policy incentives and the decreasing costs and economic maturity of renewable technologies. In the future, policies will need to focus rather on the growing intermittency of electricity supply due to the growing share of weather dependent power generation technologies (i.e. wind and solar). This requires the electricity grid to include low carbon flexibility solutions (including battery storage, pumped hydro storage and other technologies).

Thus, policies may switch from supporting certain technologies into a systematic approach in order to decarbonize the operation of the whole electricity grid. The closure of old powerplants, lag in development of low carbon flexibility solutions and insufficient investments into renewables can lead to scenarios in which natural gas (with associated emissions) would be required to fill the gap between supply and demand, and as a dispatchable energy alternative to tackle the intermittency of renewables. Nevertheless, with ambitious targets both on supply and demand sides, as well as wisely chosen balancing strategy that relies on low carbon storage solutions such as batteries and pumped hydro storage can reduce the role of natural gas as balancing and flexibility fuel.

3 Trends and evolution of the energy supply sector

The goal of this section is to give a short overview of the context and current trends in the electricity supply and oil refinery sectors.

The energy supply module consists of electricity production supplemented by sub-modules of oil refining and hydrogen production.

A major change has been going on in the power generation sector of the EU with significant increase of renewables technologies and accelerating decrease of burning of fossil fuels (Figure 1). The growing share of renewables is due to policy incentives and more and more to decreasing costs and economic maturity, while fossil fuel-based capacities are disappearing due to ageing of power plant stock and phase-out policies (Farfan and Breyer, 2017). In the EU growth of wind and solar power (photovoltaics, PV) based power generation has been significant: from 2.4 GW in 1995 to 154.3 GW in 2016, and from 0.05 GW in 1995 to 103.1 GW in 2016, respectively (European Commission, 2018a). These trends are expected to continue in the future as renewables become more competitive (IRENA, 2018) while coal power plants more obsolete. A study shows that 54% of the coal power plants in the EU has negative cashflow today and predicted to increase to 97% by 2030 with the operating cost of coal could be higher than the levelized cost of electricity (LCOE) of onshore wind by 2024 and PV by 2027, while battery storage and demand response increasingly provide auxiliary services and peak shaving (Carbon Tracker, 2017). In general, all fossil fuel-based power generation capacities in Europe are aging meaning a good chance for renewables to substitute them (Farfan and Breyer, 2017). Nevertheless, natural gas-based power generation may play a role in balancing the growing intermittency of the production due to its flexibility (Kinnon et al., 2018).

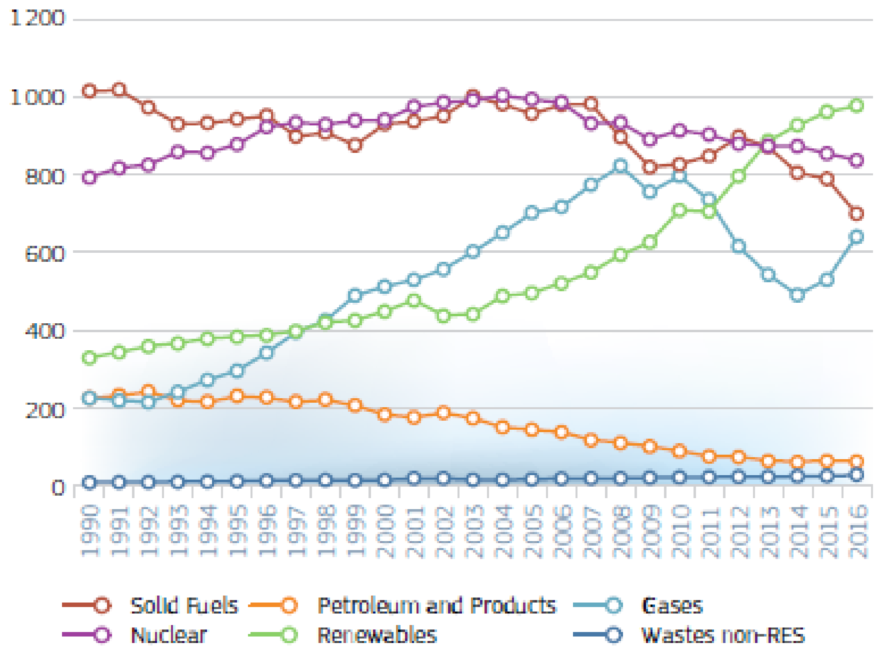

Figure 1 – Gross Electricity Generation in EU-28, 1990-2016 (TWh), source: European Commission, 2018a

Emissions included in the energy supply module are from two categories of the Intergovernmental Panel on Climate Change (IPCC) emission inventories. The main source of emissions is the public electricity and heat production (CRF 1A1a) that includes emissions from main activity producers of electricity generation, combined heat and power generation, and heat plants. Main activity producers (i.e. public utilities) are defined as those undertakings whose primary activity is to supply electricity to the public. This is the largest key category in the EU-28 and Iceland accounting for 24% of total GHG emissions in 2016 and for 86% of greenhouse gas emissions of the Energy Industries Sector (EEA, 2018). Nevertheless, between 1990 and 2016, CO_2 emissions from electricity and heat production decreased by 29% (Figure 2) and expected to decrease further as renewables are becoming main source of power generation. CO_2 is the bulk of emission, with N_2O and CH_4 emissions currently represent 0.6% and 0.4%, respectively, of greenhouse gas emissions from public electricity and heat production (EEA, 2018).

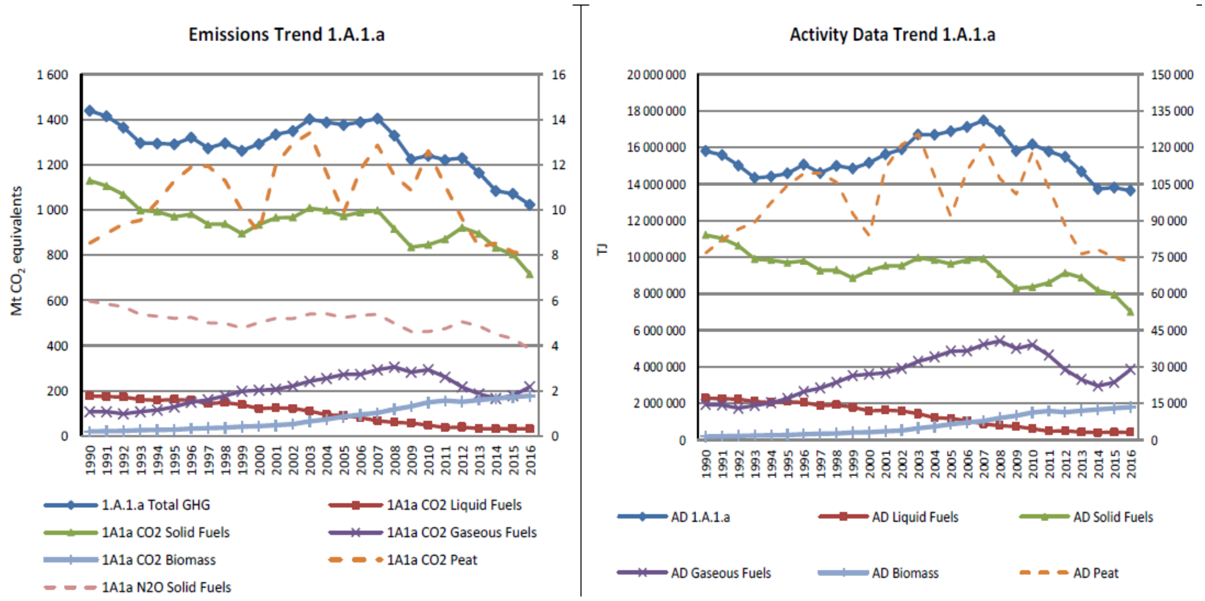

Figure 2 – Emissions from Public Electricity and Heat Production: Total, CO_2 and N_2O emission and activity data trends, source: EEA, 2018

Main contributors to those emissions are solid fuels (mainly coal) responsible for 51% even with the decline of coal use for power generation. There are three reasons behind the increase in electricity production and the actual reduction in emissions during 1990-2016: (1) improvement of thermal efficiency, (2) changes in the fossil fuel mix used to produce electricity, i.e. fuel switching from coal and lignite to natural gas and (3) growing share of renewables based technologies (Figure 3).

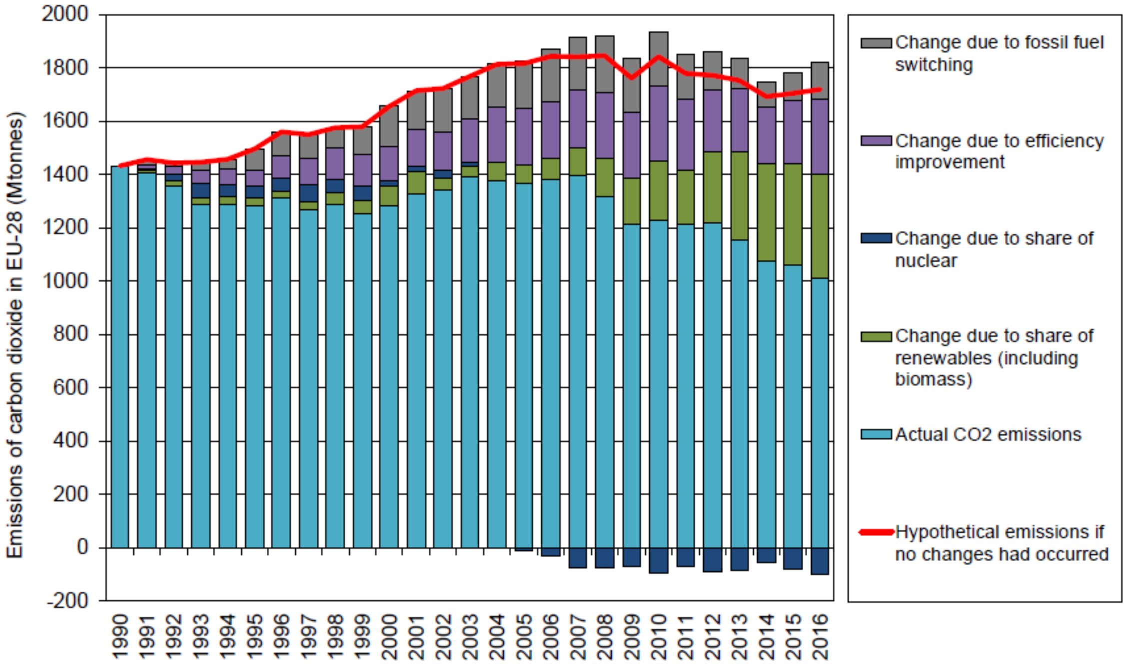

Figure 3 – Estimated impact of different factors on the reduction in CO_2 emissions from public electricity and heat production in the EU-28 between 1990 and 2016, source EEA, 2018

Carbon dioxide emissions from Petroleum Refining, also part of the energy supply module, accounted for 3% of total greenhouse gas emissions in year 2016 (EEA, 2018).

In the module, we only account for the carbon dioxide emissions of those sectors, as emissions of other gases are minor. For example, N_2O and CH_4 emissions in 2016 represented 0.6% and 0.4%, respectively, of greenhouse gas emissions from public electricity and heat production on carbon dioxide equivalent basis (EEA, 2018). The only exception is the biomass based technologies (biomass based power and biogas) integrated into our module, as for those technologies N_2O and CH_4 aligned with the handling of biomass based emissions throughout the whole EUCalc model.

3.1 Gender aspects of energy supply

The European Parliament's Policy Department for Citizens´ Rights and Constitutional Affairs highlights that "*Energy policies throughout the EU Member States appear to be gender blind and implementation appears not to adopt gender approaches limiting gender equality in the energy transition*" (European Parliament, 2019). According to a representative survey by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety and the German Federal Agency for Nature Conservation, both women and men advocate for Germany's energy transition. Differences in age, education, and income are more pronounced than sex, regarding the level of support for the energy transition (Fraune, 2015).

A longitudinal study of Fortune 500 companies found no significant increase in corporate environmental decision making for companies with woman CEOs, but saw an increase for companies with gender diverse leadership team and boards (Glass et al., 2016). Given that women make up 32% of the workforce in renewable energy, compared to 22% in the oil- and gas industry, it becomes clear that women in positions to influence the energy transition (corporate sector, public energy sector and civil society initiatives) are crucial for a successful energy transition (IRENA, 2019; C3E, 2019).

In addition, energy poverty, analysed through a gender lens, reveals a strong gender dimension referred to energy access. Women, particularly single parents and women above retirement age, are more likely than men to live in energy poverty at some stage in their life, limiting their access to renewable energy services and hindering their participation in the energy transition, e.g. to invest in citizen participation schemes in renewable electricity production (European Parliament, 2019; Fraune, 2015).

However, to better understand the nexus between gender and power, it is highly recommended that future assessments in Europe include data on sex, age and economic status.

4 Questions addressed by the module

The goal of the energy supply module is to quantify various impacts on the electricity generation system, oil refinery sector and hydrogen production in the EU-28 plus Switzerland in different scenarios. The objective of this section is to clarify the ambitions of the module.

The energy supply module takes into account different types of **impacts**: the electricity production and direct GHG emissions are computed directly in the module, other types of impacts (indirect emissions, resources use, economic impacts) are computed by other modules. The module also takes into account some impacts of the electricity system on other sectors, while sectors demanding energy carriers have serious impact on this module. Supply-demand matching of electricity and accounting for the intermittent nature of renewable electricity productions are considered in the closely linked Storage requirements module, which is documented separately (see more in Deliverable 8.5 "Storage requirements Module").

In terms of **scenarios**, the module investigates the changes in power generation technologies considering fossil fuels phase-out policies and renewable energy potentials. In order to exploit those opportunities, in some cases breakthroughs are needed – not only in technology but policy ambitions, too. Finally, technologies that are not directly related to decarbonization, and whose effects are not completely known (e.g. blockchains) are not directly integrated in the model, but its effects could be partially reproduced with combinations of levers.

Table 1 hereunder summarizes the ambitions of the energy supply module.

Table 1 – Ambitions of the energy supply module

Theme	Questions		Ambition[1]
What are the <u>types of impacts</u> we want to take into account in the model?	Energy	• Power generation: What is the total and per technology power production? What energy input is needed for this production per energy carrier? • Oil refinery: what is crude oil need of oil refinery? • Hydrogen: what is electricity and natural gas demand for hydrogen production?	Yes
	Emissions	• Direct emissions: What are the direct emissions of the power generation and oil refinery sectors?	Yes
	Products, materials & resources	• Material use: what is the resource usage of the investments into power generation?	Partially through other modules
	Economy	• Economy: What is the cost and economical impact of the different scenarios (e.g. jobs)?	Partially through links with other modules
		• Trade: costs of fossil fuels and import ratio of fossil fuels?	Through GTAP integration
	Other	• Other: Biodiversity? Health?	Partially through other modules
What are the <u>existing solutions</u> to decarbonize energy supply?	Avoid	• Impact of coal phase-out and its timing?	Yes
		• Impact of power generation technology choice	Yes
	Shift	• Impact of nuclear phase-out and its timing?	Yes
	Improve	• Impact of large share of renewables	Partially through other modules
		• Impact of power generation technology choice	Yes
Can we identify some <u>potential breakthrough</u> (technologies or societal) that could have an impact?	Improve	• What would be the impact of improved grid flexibility and DSM on the intermittency and balancing of large share renewables?	Partially through other modules
What are the <u>impacts of other sectors on energy supply</u>?	Lifestyle	• Meeting the demand for electricity, hydrogen and crude oil products via oil refining	
	Buildings	• Meeting the demand for electricity, hydrogen and crude oil products via oil refining	
	Transport	• Meeting the demand for electricity, hydrogen and crude oil products via oil refining	
	Agriculture	• Meeting the demand for electricity, hydrogen and crude oil products via oil refining	
	Industry	• Meeting the demand for electricity, hydrogen and crude oil products via oil refining	

[1] Does this module have ambition to answer that question?

5 Calculation logic and scope of module

5.1 Overall logic

The energy supply module includes the following three submodules:

- electricity generation,
- oil refinery,
- hydrogen production.

While the purpose of the oil refinery and hydrogen production subunits is only to convert the incoming demand for oil products and hydrogen into primary energy carriers, the electricity generation submodule allows the user to set the composition of power generation mix by choosing the capacity development trajectories of technologies defined as levers.

The calculation is based on a bottom-up approach to compute electricity production and GHG emissions by using historical data (sources for historical data are described in Section 6), and trajectories until 2050 (the different projection levels are described in Section 5).

The main outputs of the energy supply module are:

- The direct GHG emissions from electricity generation, oil refineries and hydrogen production;
- Aggregated, economy wide demand for coal, natural gas, oil products and crude oil;
- The electricity production per technology and per country (in the core module electricity production is not matched against demand and levers of power generation technologies are independent from each other – supply-demand matching, and balancing are considered in the storage module described in Deliverable 8.5);
- The capacities of power generation technologies installed (set by lever);
- The investment cost of the selected power generation investment pathway;
- Production cost of electricity.

The calculation logic of the electricity generation adopted here consists of five steps based on the next parameters (see Figure 4):

1. the power generation capacities per technology (in GW);
2. the capacity factor of each technology (in % expressing the annual ratio of actual operation compared to operating in 100% of time);
3. the efficiency of fossil fuel-based power generation technologies (in % expressing input-output ratio of energy);
4. the emission factor of each type of fuel used in the various technologies (gCO_2e/MJ);
5. the investment costs for installation of new power generation capacities (CAPEX), the O&M (OPEX) cost of power plants including the cost of fuel is used to calculate the cost of electricity production based on solely technology parameters; costs associated with balancing and other system impacts are considered in the storage module.

The different parameters, technologies and types of fuels are further described below in the Section 4.4.

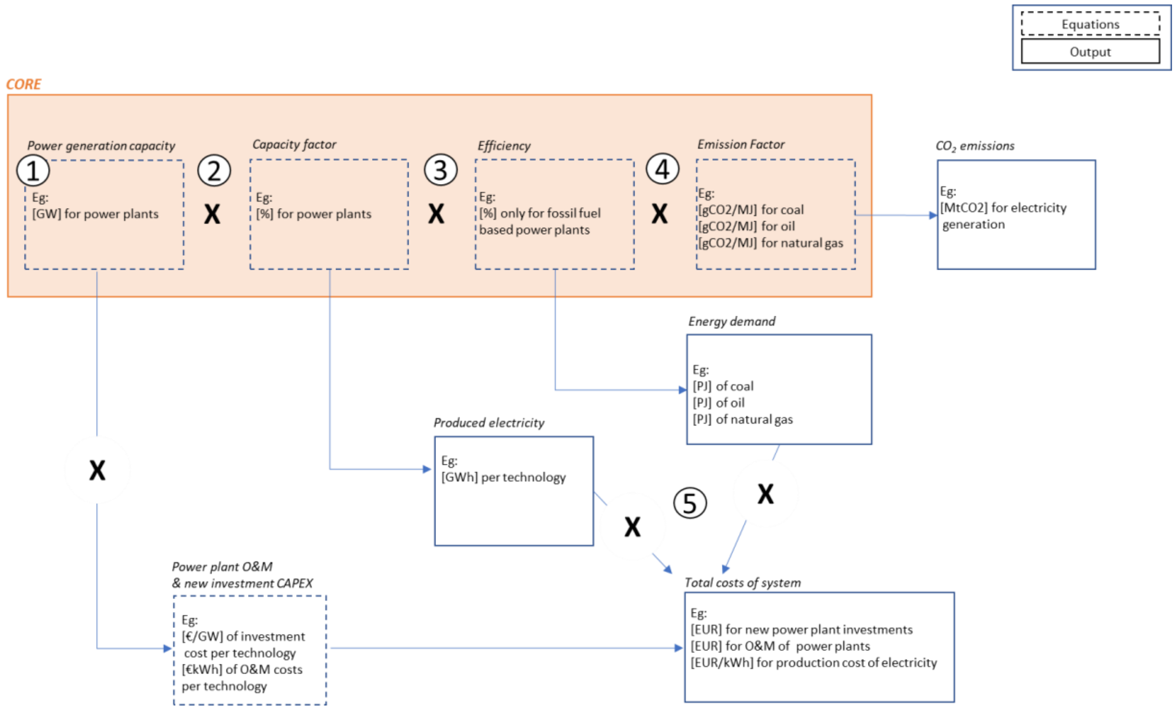

Figure 4 - Calculation logic of electricity generation.

The calculation logic of oil refinery adopted here consists of four steps to successively estimate (see Figure 5):

1. aggregated demand for each oil product (diesel, kerosene, gasoline and heating oil) from each sector (as input, TWh);
2. ratio of the demands of different oil products is different then the refinery products output ratio (i.e. the ratio of certain oil products compared to the total refinery output), thus demand and supply are matched based on the diesel demand (see justification later) for the other products gaps are calculated and assumed to be imported or exported;
3. based on process parameters calculating needed crude oil intake (TWh) and needed oil refinery utilisation rates of the projected capacities;
4. based on the used energy calculating direct emissions from the oil refinery process.

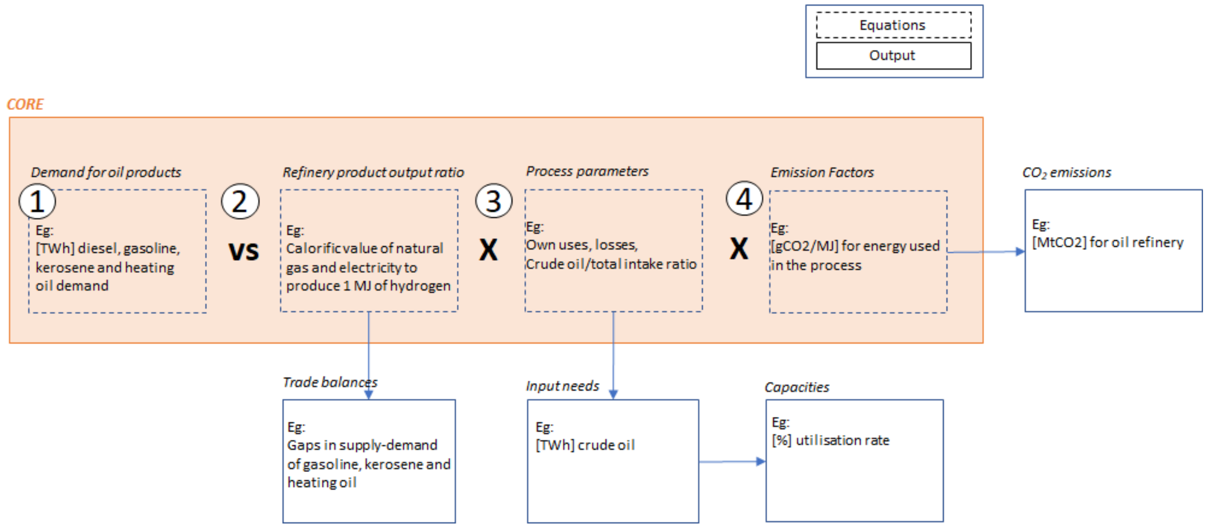

Figure 5 – Calculation logic of oil refinery

The calculation logic of the hydrogen production adopted here consists three steps based on the next parameters (see Figure 6):

1. aggregated demand for hydrogen collected from each sector (as input from other modules, GWh);
2. calculating input needs based on the specific energy demand to produce one calorific unit of hydrogen (energy unit/energy unit);
3. calculating direct process emissions based on the emission factor of natural gas used as input (gCO_2e/MJ).

The different parameters, technologies and types of fuels are further described below in the Section 4.4.

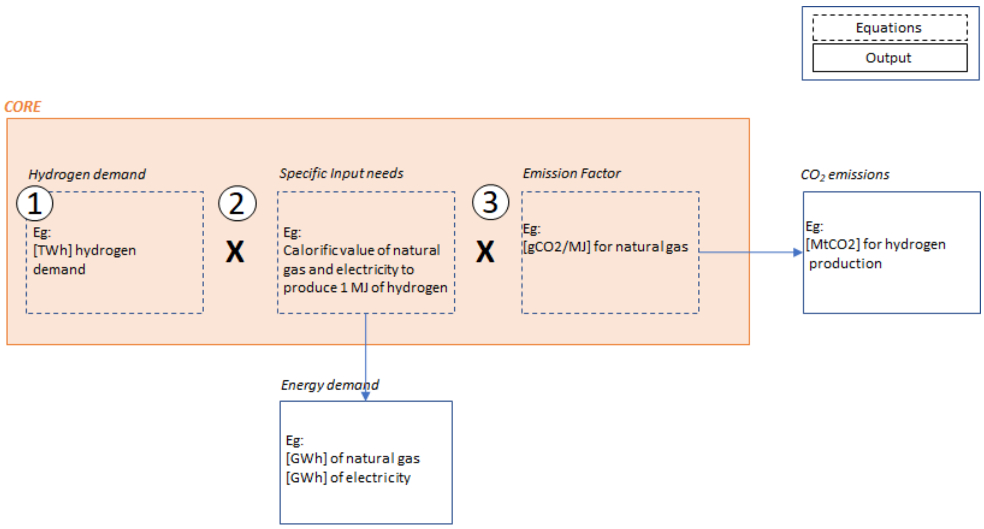

Figure 6 – Calculation logic of hydrogen production

The following sections will dive deeper into the calculation logic of the submodules.

5.2 Scope definition

5.2.1 Electricity production

Figure 7 defines the scope of the electricity generation module in terms of:

- The technologies included in the model;
- The types of energy carriers considered.

Technologies:

- Solar: PV and CSP
- Wind: On- and off-shore
- Other RES: Hydropower, Ocean, Geothermal
- Fossil fuel based generation: Coal, Oil, Natural gas
- CCS
- Nuclear

Energy vectors:

- Electricity
- Coal
- Oil
- Natural gas

Figure 7 – Scope definition of the electricity production module: technologies and energy carriers

5.2.2 Oil refinery

Figure 8 defines the scope of the oil refinery module in terms of:

- The technologies included in the model;
- The types of energy carriers considered.

Technologies:

- Oil refinery
- CCS

Energy vectors:

- Diesel
- Gasoline
- Kerosene
- Heating oil
- Crude oil

Figure 8 – Scope definition of the oil refinery module: technologies and energy carriers

5.2.3 Hydrogen production

Figure 9 defines the scope of the oil refinery module in terms of:

- The technologies included in the model;
- The types of energy carriers considered.

Technologies:

- Natural gas reforming

Energy vectors:

- Hydrogen
- Natural gas
- Electricity

Figure 9 – Scope definition of the hydrogen production module: technologies and energy carriers

5.3 Interactions with other modules

The energy supply module collects the energy demand from all the demand side modules, as well as parameters of technologies applied from the technology module and gives data to the buildings, storage and socio-economics modules, as well as the pathway explorer (see Figure 10).

In general, the module turns the demand of different forms of energy (such as electricity, oil products and hydrogen) into primary energy demand which, after aggregation is forwarded to the Minerals module to compare them to the available resources. Noteworthy, that there is no supply-demand matching performed in the supply module. Electricity supply-demand matching takes place in the closely linked storage module that not only considers the supply-demand gap but also the fluctuations both on the production and demand side.

Details of the function of each module linked to the energy supply module are described in the respective documentation.

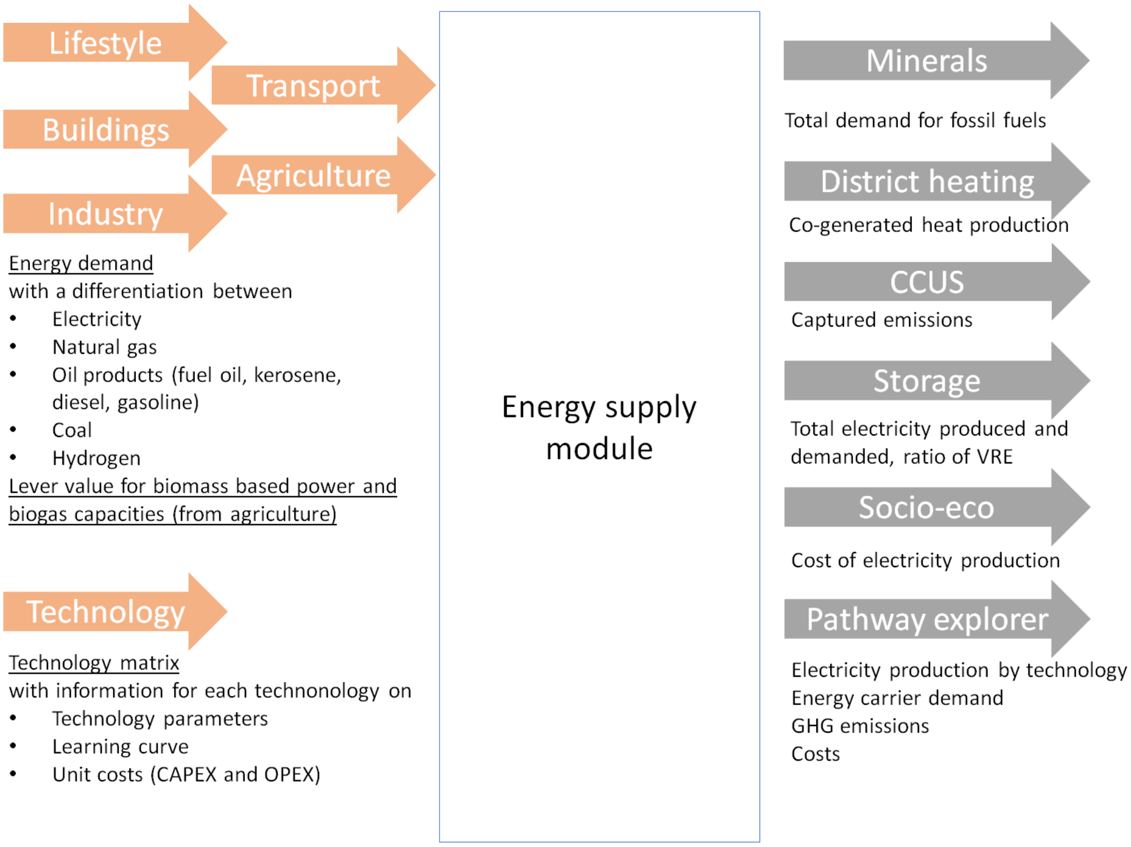

Figure 10 – Interactions of the energy supply module with other modules

5.3.1 Inputs

The main inputs are the demands for the different forms of energy. These values are controlled by the lever settings in the other modules influencing behaviour of consumers, status of the building stock, ways of transportation, forms of industrial production, as well as agricultural activities.

5.3.1.1 Lifestyle

The lifestyle module forwards the amount of electricity needed for the operation of server farms. This variable is used in the supply module for the calculation of the aggregated demand for electricity forwarded to the storage module.

5.3.1.2 Buildings

The buildings module forwards the electricity demand of the building sector. This variable is used in the supply module for the calculation of the aggregated demand for electricity forwarded to the storage module.

Additionally, this module demands oil, coal and natural gas used in the buildings. These energy carriers are used in the supply module to calculate the total demand for those energy carriers, which are forwarded then to the minerals module.

5.3.1.3 Transport

The transport module forwards the electricity demand of the transport sector. This variable is used in the supply module for the calculation of the aggregated demand for electricity forwarded to the storage module.

Also, the transport module demands refined oil products (diesel, gasoline and kerosene) as input for the oil refinery calculation. Demand for hydrogen is also coming from the transport sector used in the hydrogen production submodule where converted for electricity and natural gas need to produce that amount of hydrogen.

Additionally, the transport module forwards the natural gas usage in transportation. This energy carrier is used in the supply module to calculate the total demand for that energy carrier forwarded to the minerals module.

5.3.1.4 Agriculture

The agriculture module forwards the electricity demand in agriculture. This variable is used in the supply module for the calculation of the aggregated demand for electricity forwarded to the storage module.

Also, the agriculture demands refined oil products (diesel and gasoline), which after aggregation are an input for the oil refinery submodule.

Additionally, the agriculture module forwards the oil and natural gas usages in agriculture. These energy carriers are used in the supply module to calculate the total demand for those energy carriers, which are forwarded then to the minerals module.

As the multiple uses of biomass are assessed in the agriculture module along different targets and priorities, this module includes a lever for the biomass based power and biogas capacities. While the feedstock side and its implications are assessed in that module, the value of the lever is forwarded to the supply module to calculate the electricity production and associated outputs.

5.3.1.5 Industry

The industry module forwards the electricity demand in industry. This variable is used in the supply module for the calculation of the aggregated demand for electricity forwarded to the storage module.

Additionally, industry demands oil, coal (including coke demand) and natural gas. These energy carriers are used in the supply module to calculate the total demand for those energy carriers, which are forwarded then to the minerals module.

5.3.1.6 Technology

The technology module provides the next parameters for the technologies:

- investment cost (CAPEX) and operation and maintenance cost (O&M) without fuel costs, both as function of technology specific learning rates,
- fuel cost,
- lifespan of technologies,
- efficiency of the fossil fuel and biomass based technologies expressed as the ratio of output amount of electricity per the input energy carrier in terms of calorific value,
- emission factors for the fossil fuel-based technologies expressed as the amount of CO_2 emitted per input calorific value.

5.3.2 Outputs

5.3.2.1 Minerals

The total, economy wide fossil fuel demand, as primary fossil energy demand is forwarded to the minerals module to compare them against resources.

5.3.2.2 District heating

Volume of cogenerated heat in power generation as one source of heating energy is forward to the district heating module that models the district heating systems.

5.3.2.3 Carbon capture utilization and storage

The amount of captured emissions is forwarded to the CCUS module where its sequestration or utilisation are assessed. The scope of the CCUS module, as described in more details in its own documentation is to model the process of sequestration and utilization of the CO_2 captured in the power generation, oil refinery and industry sectors.

5.3.2.4 Storage requirements module

Supply and demand for electricity, total demand for electricity and ratio of wind and PV generation technologies are forwarded to the storage requirements module. Those outputs are used in the storage module to calculate the necessary capacities of natural gas for meeting demand (if undersupply) and the storage capacities considering the intermittency of renewable based power generation. Natural gas plays a role of buffer in the balancing of electricity supply and demand with the consideration that in the energy supply module no new natural gas based capacities are proposed, solely the phase out of the existing ones due to ageing.

5.3.2.5 Economic sector costs

The module provides the cost of electricity production (in terms of €/kWh).

5.3.2.6 Pathway explorer

The pathway explorer receives the production capacities of each technology, the produced electricity per technology with associated emissions, overall energy demand per carrier, GHG emissions and overall costs.

5.4 Detailed calculation trees

5.4.1 Electricity production

The calculation tree presented hereafter represents the steps one to four of Figure 1.

This calculation is carried out on country level, however, not every technology is present in every country depending on geography and policies.

5.4.1.1 Electricity generation capacities and their yearly production

The aim of steps 1 & 2 is to calculate the electricity production capacities for every five year between 2015-2050 considering lever choices and decommissioning of base year capacities, as well as to compute the produced electricity by the capacities actually working in year N, as shown in Figure 11.

1 & 2 ***Electricity generation capacities and electricity production***

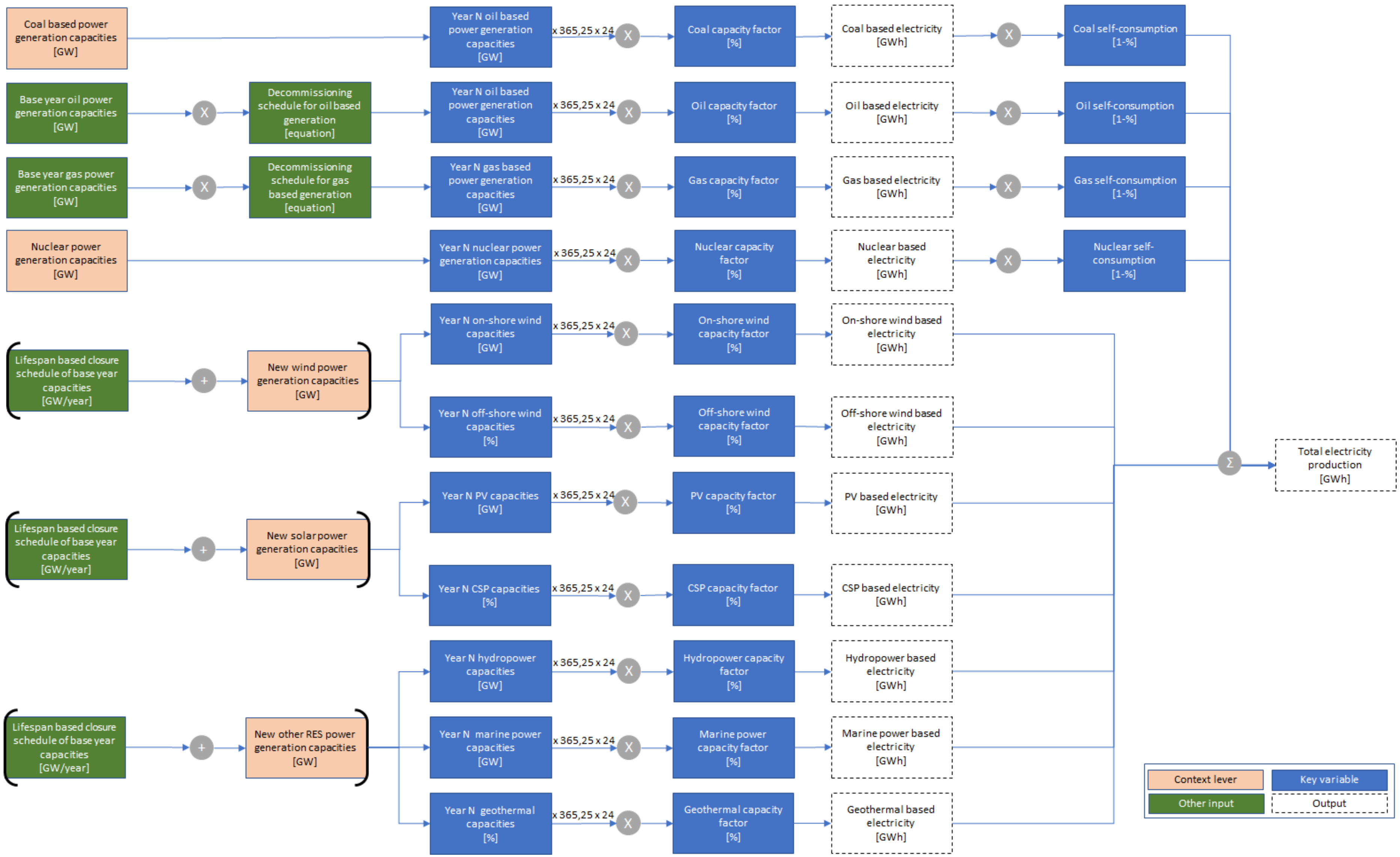

Figure 11 – Calculation tree to determine the electricity generation capacities and their yearly production

A key feature in this calculation is how the decommissioning of the base year capacities is considered, which is differently managed by technologies as detailed here:

- For nuclear and coal-based power plants separate levers were defined, the level choice determines the timing of closing the existing (i.e. 2015) power plant stock. The rationale is that coal and nuclear phase-out policies are high on the agenda in many countries, thus the EUCalc can add to this debate by showing different schedules and their impact as per level choice. Moreover, coal power plants are responsible for the highest share of emissions in power generation. It is thus a real policy question how the lock-in inherited with the ageing power plant stock can be tackled. As detailed in the lever chapter, these levels are defined on country level considering the actual country-specific policies towards those two technologies.
- For oil and natural gas-based power plants, standard equations based on the work of Farfan and Breyer (2017) were defined and applied in each country. As cited from Farfan and Breyer (2017), in the case of oil-fired capacities, the European average age of operational oil power plants is just over 33 years compared to the global weighted average age of decommissioning of oil power plants with 34 years. This explains the soon expected decay in capacities, with 74.5% of the European oil-fired capacities expected to be out of commission already by 2024, 78.3% by 2030 and 100% by 2050. The average age of decommissioned gas-fired power plants is 34 years and 7.4% are still in operation after 45 years of operation. The European average age of operating gas-fired power plants is 21 years, whilst slightly less than 18 years is the global average, the lowest of the non-renewable technologies. According to the expected operational lifetime, 48.6% would be decommissioned by 2030 and 100% by 2050 following an almost linear decommissioning pattern as shown in Figure 12.

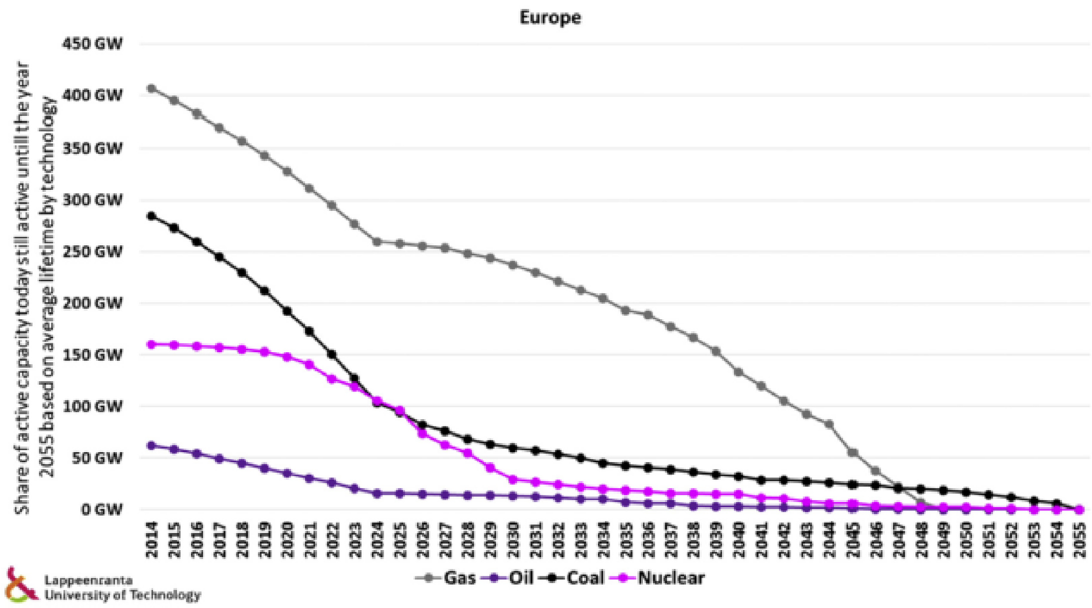

Figure 12 – Projected decommissioning of non-renewable capacities in Europe, from Farfan and Breyer (2017)

In order to calculate the actual capacities still in operation each year, the closure rates as cited above were applied on the base year power plant stock of the technology. The original work provides closure ratios for 2024 (only for oil), 2030 and 2050 (see above), while values in between were calculated by linear interpolation in line with the patterns observed on Figure 12. By using the values, the ratio of the base year stock still in operation is shown in Table 2. There are no differences between levels in the decommission rates of existing natural gas and oil-based power generation capacities, regardless the level choices, the above closure patterns are applied.

Table 2 – Survival rates for oil and natural gas based power generation capacities in Europe

	Base year	2024	2030	2050
Oil based capacities	100%	25,5%	21,7%	0%
Natural gas based capacities	100%	n.d.	51,4%	0%

Oil based power generation is already a minor part of the power plant stock in the EU, as well as in general, investment in thermal capacity of all types has slumped in Europe (IEA, 2019), we do not assume any new oil based capacities, while new natural gas based capacities are added as balancing power in a mechanism implemented by the storage module. This depends on the gap between electricity supply and demand, as well as the amount of balancing power needed, see Deliverable 8.5.

- For renewable based power generation capacities, as most of the operating stock in the base year was installed in the period of 2000-2015, lifespan-based closure schedule was created based on lifespan values from literature. In details, differences of capacities per technology and per country of every fifth year between 2000 and 2015 were calculated as new additions and removed in that future five year period, which corresponds to the lifespan. Nevertheless, those capacities are automatically replaced by new installations of the same technologies with calculating CAPEX values as the new capacities enter at the same time the old ones went down.

The output of this calculation step is the annual amount of electricity produced per technology and aggregated per country. All the levers (i.e. capacities of each technology) defining this amount are independent and not linked to electricity demand, thus the modelling provides the full flexibility of creating electricity supply pathways. The correction to meet the demand and account for intermittency of high share of renewables takes place in the storage requirements module.

Different inputs are required to compute electricity production by technology:

- Historical capacities and future trajectories of capacities as levels;
- Lifespan of renewables based power generation technologies;
- Capacity factors of technologies;
- Self-consumption of certain technologies.

These parameters are further discussed later.

5.4.1.2 Energy carrier use and emissions of electricity production

The goal of these steps is to define the energy carrier use of power generation technologies, as well as to calculate the direct emissions of the whole power generation sector. This emission is corrected by the ratio of carbon captured as the user sets the relevant lever. As capturing the CO_2 emissions has energy penalty, increased self-consumption factors are applied. Accounting for the increased own consumption of power plants due to carbon capture is applied on the same ratio of electricity produced by emitting power plants as the actual ratio of CO_2 captured. This means, if for example 10% of emissions are captured, than 10% of the produced electricity is charged by the higher own consumption due to carbon capture. Mathematically, this is implemented by deducing the produced, available electricity with the difference of the original own consumption and the increased one due to capturing the emissions.

Practically, these steps are only calculated for the capacities of fossil fuel based generation technologies demanding fuels leading to emissions (thus, the total direct emissions of the power generation sectors are equal to the emissions of fossil fuel based power plants), see Figure 13.

The outputs of these steps are:

- Demand for fossil energy carriers (oil, coal and natural gas);
- Emissions resulting from the use of that amount of energy carriers based on the emission factors defining the amount of CO_2 emitted via burning one calorific unit of the given energy carrier.

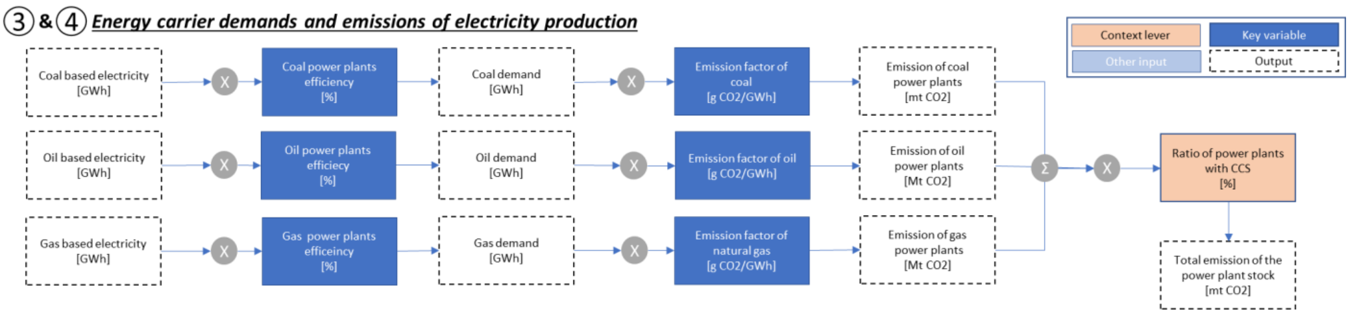

Figure 13 – Calculation tree to determine the energy carrier demand and related emissions of electricity production sector

Though using the same calculation mechanism, there is difference in the efficiency parameter for the existing power plant stock as of 2015 and the new builds after. For the base year capacities and their decommissioning, the historical dataset is used, which characterizes the efficiency of the operating power plant stock on country level. Aligned with the decommission schedule of the power plant stock this value is used for any leftovers from base year capacities. For new installations, efficiencies are defined on technology level using the same value in all countries. As efficiency is improving, the year of installation is indexed and the efficiency value at the time of installation is used through the whole lifespan of the technology.

Different inputs are required:

- The efficiency of power plants describing the input-output ratio in terms of energy equivalent;
- Ratio of emissions captured by CCS as lever input;

- The emission factors of input fuels used.

These parameters are further discussed later.

5.4.1.3 Calculating biomass-based electricity and aggregating supply

Biomass and biogas based power generation is calculated as the other renewables shown on Figure 11. The lever defining those capacities is implemented in the agriculture module, thus only the actual value of the lever is forwarded to the energy supply module on the interface. From the perspective of the modelling, solely biomass burning and co-firing is not differentiated. The needed capacities, to process the available biomass designated for electricity production can be standalone power plants or considered as additional capacities within a coal-based power plant.

Based on the capacity factor values then the produced electricity, as well associated emissions and co-generated heat production are computed. Using biomass for power generation and biogas are considered as climate neutral, thus CO_2 emission is set to zero unless carbon capture is applied when negative CO_2 emission is recorded. Following the logic of the whole EUCalc model N_2O and methane emissions are also calculated for biomass and biogas based power. Heat is calculated as described in chapter 7.1.7.

Unlike the other technologies, biomass-based electricity production is constrained by the biomass availability for the given purposes. Therefore, the needed feedstock for power generation purpose, based on the lever setting, is calculated in the agriculture module where available amount for a given purpose is defined. In the agriculture module, the production of energy crops and imports are set by the lever setting and used as buffer variables. Nevertheless, a specific lever setting allows the user to not use any crops for bioenergy purposes. In that setting, either sustainably available resources are enough to supply the biogas demand, or a warning is sent to the user to inform about the pathway inconsistency in terms of resource availability.

Total electricity production is aggregated on country level and complemented with the amount of electricity produced on biomass basis. After that the total electricity produced is corrected with the network losses (Figure 14). The available amount of electricity per country is forwarded to the storage module together with the total demand for electricity aggregated from the other, demand side modules in order to calculate the supply-demand gap. Within the EU electricity flows are also considered in the storage requirements module as a tool to match supply with demand.

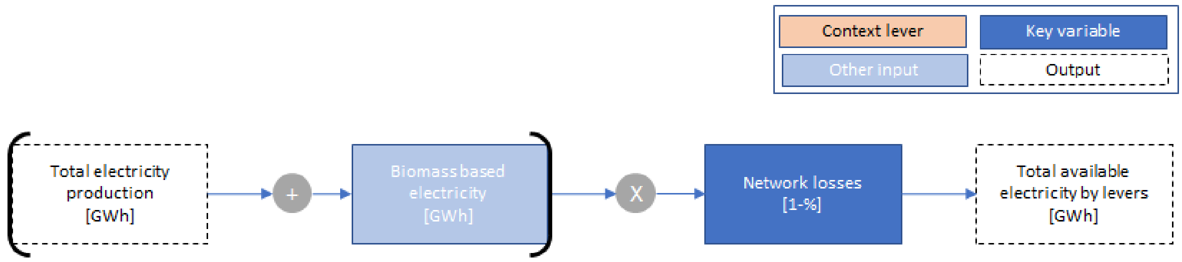

Figure 14 – Aggregating electricity production and accounting for gap between supply and demand on EU plus Switzerland level
The 1-% mark means that the produced electricity is multiplied by the difference of the actual network losses and 100%, i.e. as a result of multiplication the outcome will be the electricity produced minus the network losses.

Different inputs are required:

- Lever value for biomass for biogas and biomass-based electricity production capacities as input from the agriculture module;
- Electricity demand from demand side modules;
- Network losses.

Network loss is further discussed later.

5.4.2 Cost of electricity production

Like the other modules, cost calculation is linked to the technology module. The cost calculation uses unit costs for technology CAPEX and OPEX from the technology database. The evolution of those unit costs is expressed by applying a learning rate, i.e. the reduction of the cost as the installed capacity doubles. For fossil fuel-based electricity production technologies and nuclear power plant, no learning rate was assumed but a trajectory between fixed CAPEX and OPEX cost in 2015 and 2050. Exact values and sources can be found in section 6. The unit costs then are multiplied by the actual capacities or production. Same is applied for the fuel costs, where the unit costs of fuels are imported to the model. All unit costs are expressed in 2015 currency.

As the storage module alters electricity production and adds additional capacities and technologies, the cost of electricity is calculated there, considering all the other capacities producing electricity.

5.4.3 Oil refinery

The oil refinery submodule collects the demand for oil products from the demand sectors with the following energy carriers covered: kerosene, gasoline, diesel and heating oil. The demand is aggregated on EU level per oil product.

Oil refining is the processing of crude oil into several useful hydrocarbon products, where the output products portfolio depends on the type of crude oil processed and the configuration of the refinery (Aitani, 2004). This also means that the actual demand portfolio (i.e. shares of different oil products in the total oil product demand) does not necessarily match the products' output ratio of oil refineries working in that geographical coverage. This leads to the export or import of certain oil products to meet the demand. From a modelling perspective, two different portfolios of energy carriers need to be matched (i.e. actual demand versus product output ratio) in order to be able to model the European refining sector to project crude oil need and related emissions.

In Europe, tax incentives and structural trends in the transport sector are responsible for an increasing mismatch between refinery production and demand, with negative implications for security of supply and the environment (FuelsEurope, 2019). As shown by the net trade flows (Figure 15), while the EU has a significant excess of gasoline production capacity, it is still unable to meet the regional demand for diesel, heating gasoil and jet fuel.

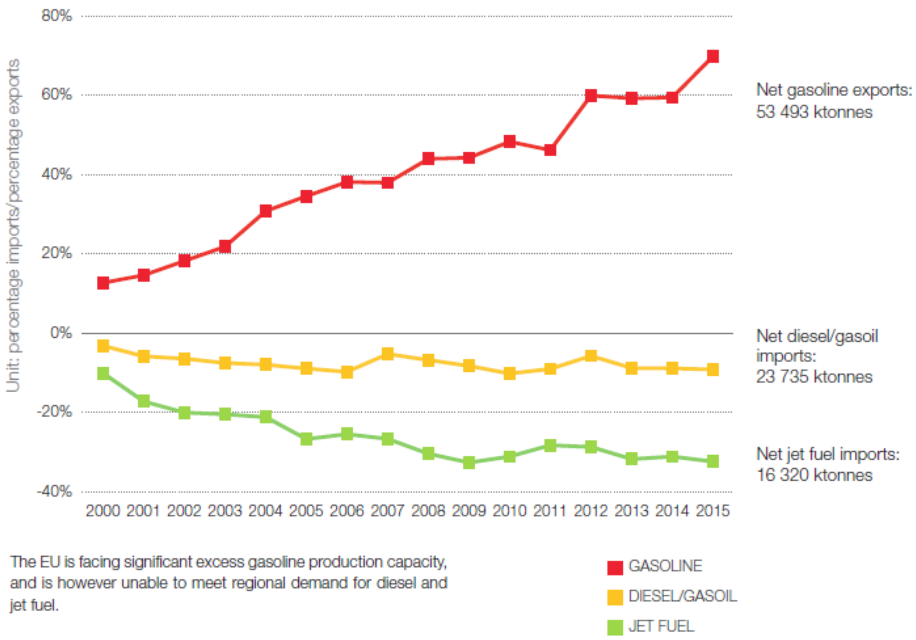

Figure 15 – EU net trade flows for refined products, source: FuelsEurope, 2017

This situation, as confirmed in stakeholder discussion, is difficult to change due to technical configuration and usual supply routes of crude oil, which deliver the type of crude that the European refineries are adjusted to. Due to this, in the calculation the aggregated demand for diesel is matched with the diesel output of refineries defining the production volume of other oil products, too. The rationale behind is, that diesel production and demand is the closest to net zero trade flow. Due to the rigid structure and technology of the oil refineries, we do not expect significant changes in the product output ratio (this assumption was also confirmed through personal discussion with an expert of the oil refinery sector). Nevertheless, we cannot exclude changes in the ratio of demands for oil products but still, confirmed by the expert, the approach can work on a longer period.

By fixing the amount of diesel output (equal to the demand), the output of other oil products was calculated by the product ratio of the European oil refinery stock. Annual production volume of secondary products (LPG, Naphtha, Gasoline, Kerosenes, Diesel, Fuel oil and other oil products) was gathered from the JODI Oil World Database (JODI-Oil, 2019) per country covered in the EUCalc model. The ratio of each product was calculated by dividing the amount of each product by the total product amount. Applied ratios in the calculation, as shown in Table 3, are averages of the period of 2002-2017 and all countries involved in the EUCalc model.

Table 3 – Ratios of oil products used in the EUCalc oil refinery calculation based on data from JODI Oil World Database

Oil product	Ratio of output
LPG	2.90%
Naphtha	2.75%
Gasoline	22.99%
Kerosenes	5.73%
Diesel	43.00%
Fuel oil	16.79%
Other oil products	5.85%
Total	100%

While diesel output is matching the diesel demand, there can be gaps between supply and demand in case of the other products. These gaps are calculated and assumed to be filled up by imports to meet demand or products are exported in case of excess production.

In order to calculate the necessary amount of crude oil and total refinery intake as inputs to the refineries, the following factors are considered in the calculations and kept constant to 2050.

- energy use of refineries is fixed at 5.11% of the refinery intake and fully covered from it. This percentage is calculated from 2015 values on EU level from EU refinery energy use divided by the EU refinery total intake, both data by Eurostat (Eurostat, 2017);
- losses are expressed as ratio of total intake and defined as difference of *refinery output (incl. losses and energy use)* and *refinery total intake*, both data from JODI-Oil World Database (JODI-Oil, 2019) from 2015 averaged on EU level with a value of 1,14%;
- crude oil is 89,9% of the total refinery intake calculated based on the data from JODI-Oil World Database (JODI-Oil, 2019) from 2015 averaged on EU level.

CO_2 emissions are calculated based on emission factors defined in the Annual European Union greenhouse gas inventory 1990–2016 and inventory report 2018 (EEA, 2018) for the energy use of the refineries (equal to 5,11% of the total refinery intake). The EEA (2018) differentiates two emission factors for the operation of oil refineries: 67 t CO_2/TJ for liquid fuels, that represent 76.9% of all fuels used in the refining of petroleum and 55,7 t CO_2/TJ for gaseous fuels, almost fully account for the remaining part (22.8%) of the activity data (EEA, 2018). These two emission factors are applied to calculate emissions by sharing the certain parts of energy use. Energy use is completely covered from the refinery intake. The operation of the oil refinery yields the oil products but not uses it, therefore not the emission factors of the different oil products are applied here – those are outcomes of the process and not burned in the process.

So far, all the output data are EU level values and in order to calculate country level refinery inputs and emissions, the total values are shared between countries in the ratio of oil refinery capacities in 2015 (considering the capacities of EU and

Switzerland as 100%), as not every country in the modelling has oil refineries. Table 4 shows the refinery capacities per country based on the database of CONCAWE (CONCAWE, 2019), countries modelled, but not included in the table, do not have oil refinery capacity.

Table 4 – Primary refinery capacities in Europe in 2015, source: CONCAWE website

	Refinery capacity	
	Mt/a	%
Austria	10.40	1.33%
Belgium	39.10	5.01%
Bulgaria	5.80	0.74%
Croatia	8.50	1.09%
Czech Republic	8.80	1.13%
Denmark	8.50	1.09%
Finland	13.10	1.68%
France	94.80	12.16%
Germany	120.00	15.39%
Greece	23.40	3.00%
Hungary	10.90	1.40%
Ireland	3.60	0.46%
Italy	104.40	13.39%
Lithuania	9.50	1.22%
Netherlands	63.00	8.08%
Poland	27.60	3.54%
Portugal	16.20	2.08%
Romania	16.30	2.09%
Slovakia	5.30	0.68%
Spain	75.90	9.73%
Sweden	21.90	2.81%
Switzerland	5.80	0.74%
United Kingdom	87.00	11.16%
Total	779.80	100.00%

Nevertheless, oil refinery capacities are going to evolve between 2015 and 2050 based on the 2017 OPEC World Oil Outlook (OPEC, 2017), shown in Table 5.

Table 5 – Crude unit throughputs and utilizations in Europe, source: OPEC, 2017

	2016	2020	2025	2030	2035	2040	2045*	2050*
Total crude unit throughputs, million barrel/day	12.5	13.1	12.4	12.0	11.7	11.0	11.0	11.0
Total crude unit throughputs, mtoe/a	622.8	652.6	617.8	597.8	582.9	548.0	548.0	548.0
Crude unit utilization, %	72.9	78.0	76.0	73.6	71.6	67.1		

*own estimation

Based on the capacities and the needed crude oil intake, the utilisation rate (percentage of calendar day capacity) is calculated as output indicator. Based on FuelsEurope, a utilisation rate around 85% is optimal from an economical point (FuelsEurope, 2017). Therefore, this output can help policymakers to understand the impact of decarbonisation of the European oil refinery sector. Nevertheless, as shown in Table 5 above, long-term projections predict decreasing utilisation rates. The whole process described above is shown in Figure 16.

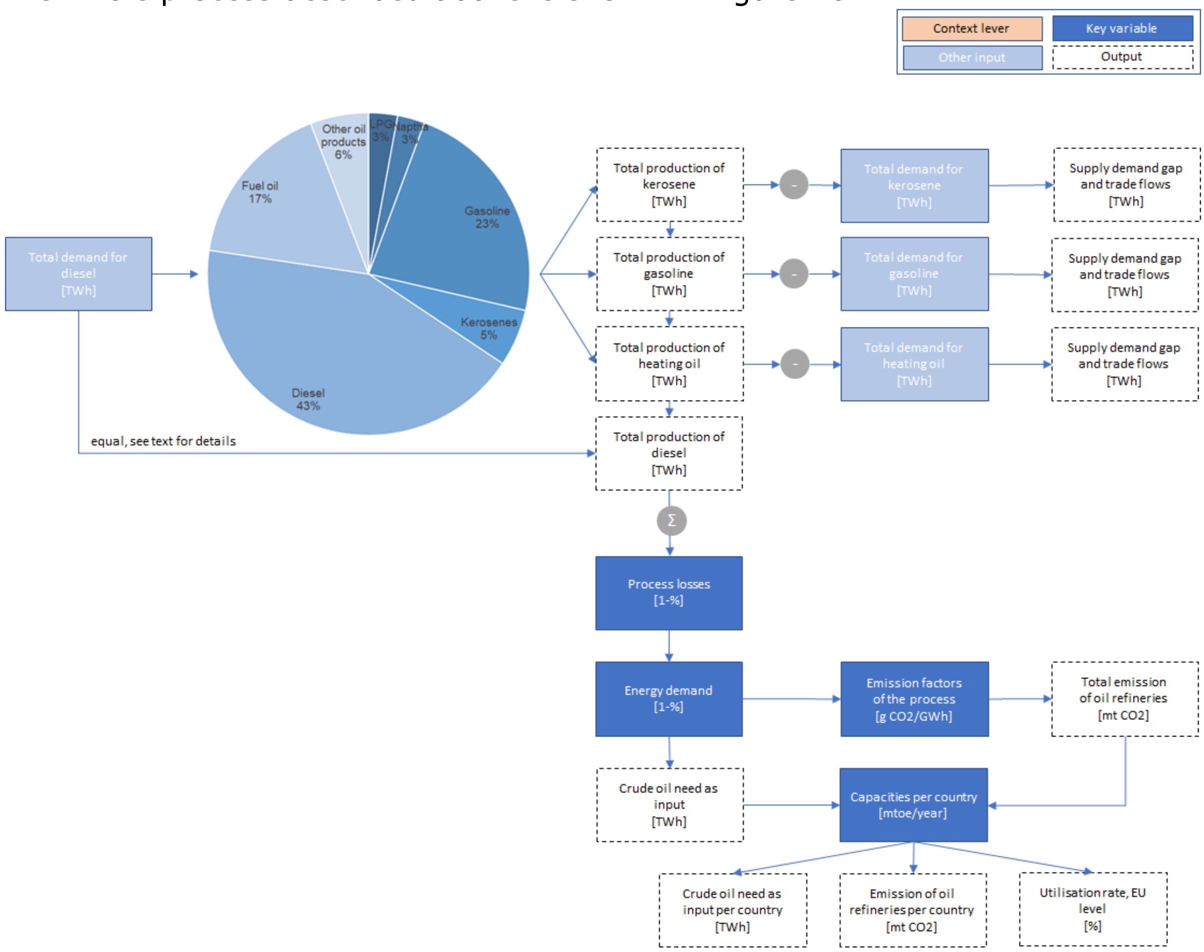

Figure 16 – Calculation tree of the oil refinery submodule

Annual demand for diesel, gasoline, kerosene and heating oil from different sectors is needed as input.

5.4.4 Hydrogen production

Hydrogen demand from all sectors (relevant for industry and transport) is collected and used as input to calculate necessary energy and input energy carriers to produce the required amount of hydrogen.

The calculation method is based on the Hydrogen Tools Portal (H2Tools)[2] developed by the Pacific Northwest National Laboratory with support from the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE). The goal of H2Tools is to support implementation of the practices and procedures that will ensure safety in the handling and use of hydrogen in a variety of fuel cell applications.

The exact calculation methodology is adapted from the Hydrogen Production Energy Conversion Efficiencies table[3] of the H2Tools portal that contains energy inputs, energy outputs, and overall conversion efficiencies for various hydrogen production processes.

In the module, natural gas reforming technology was considered as industrial scale process to produce the needed hydrogen. Based on the Hydrogen Production Energy Conversion Efficiencies table of the H2Tools portal, this process has an overall efficiency of 72% (highest among the technologies investigated) and needs 156 250 Btu of natural gas and 1 942 Btu of electricity as inputs to produce 1 kg of hydrogen (equal to 113 940 Btu of energy). Therefore, the hydrogen demand was multiplied by 156 250/113 940 to calculate natural gas need, and by 1 942/113 940 to calculate electricity need of the process. Demanded natural gas is used to calculate direct emissions, while demanded electricity is added to the total electricity demand.

The demand for hydrogen from other modules is required as input.

5.4.5 Fossil fuel resources

This step aggregates all the demand (including the fossil fuels needed for electricity production, oil refinery and hydrogen production) of coal, natural gas and crude oil in order to forward them to the minerals module to see resources consumption.

[2] https://h2tools.org/

[3] https://h2tools.org/sites/default/files/imports/files//Hydrogen_Production_Efficiencies_Current.xls

6 Description of levers and ambition levels

6.1 Lever list and description

Emissions from electricity production are the results of the amount of electricity needed (depending on demand side actions) and of the mix (i.e. ratio or capacities in absolute value) of technologies generating that amount of electricity. This latter is subject of policy debates and different targets. These policies or intentions, let them be national or EU level, start from the composition of the current electricity generation mix and draw scenarios following a specific policy intention (for example phase-out, maintenance or reaching a target expressed as percentage of demand).

In view of the EU decarbonisation target, in case of coal, many EU countries have policies to phase-out coal, as show below on Figure 17. Hereby, the opportunity to investigate the different timings of phase-out and its impact on decarbonisation pathways is provided. Due to different concerns, nuclear power is also target of phase-out considerations in some countries, while others want to maintain it and consider it as an instrument for decarbonisation. Impact of nuclear policies (i.e. phase-out or maintenance) and their timing is also an important aspect of developing decarbonisation pathways.

Figure 17- Coal phase-out plans in Europe as of January 2018, source: BNEF, 2018

While there are different approaches for nuclear power, EU Member States unanimously look at renewables for decarbonizing their electricity mix. EU level policies, starting with the Renewable Energy Directive (RED) (European Commission, 2009), defined different targets for renewables expressed as ratio in electricity demand to be supplied. The EU target for 2030 includes at least a 27% share of renewable energy consumption (European Commission, 2014a). Nevertheless, the starting position, current situation and more importantly, potential that can be exploited for renewable based electricity vary among Member States. The Electricity generation module allows users to investigate different amounts of new capacities of renewable based electricity generation up to the total exploitation of the potential, in order to learn the impact and reasonable investment that meets demand in a sustainable way.

Following this logic and adding to the policy debates capacity values of technologies are used as levers. Of course, most countries do not have all the technologies listed as levers. Table 6 summarizes the proposed levers.

Table 6 – List of levers for electricity generation submodule

	Lever	**Brief description**
1.	Wind power generation capacity additions [GW]	Capacity additions of wind power generation, including and differentiating on- and off-shore technologies.
2.	Solar power generation capacity additions [GW]	Capacity additions of solar power generation, including and differentiating PV and CSP technologies.
3.	Changes in nuclear power generation capacities [GW]	Changes in nuclear power capacities and their timing considering the policies of the countries.
4.	Changes in coal power generation capacities [GW]	Changes in coal power capacities and their timing considering the policies of the countries.
5.	Ratio of emission from power plant and oil refinery sectors captured [%]	Ratio of CO_2 emission from fossil fuel based power plant capacities and oil refineries captured
6.	Other renewables [GW]	Composite indicator including capacities of geothermal, marine and hydropower. The reason of combining those technologies was, that there are only limited countries with potential both in geothermal and marine power generation, thus the lever most likely relates to one of those depending on the country. While hydropower contributes the most to the renewable power generation in EU, further exploitation potential is limited due to already established infrastructures.

6.2 Definition of ambition levels

6.2.1 Level 1, 2, 3, 4

The definition of ambition levels is shown in Table 7.

Table 7 – Definition of ambition levels and list of levers with that kind of ambition levels

Level 1	**Level 2**
This level contains projections that are aligned and coherent with the observed trends.	This level is an intermediate scenario, more ambitious but not reaching the full potential of available solutions.
Level 3	**Level 4**
This level is considered as very ambitious but realistic scenario, given the current technology evolutions and the best practices observed in some geographical areas.	This level is considered as transformational and requires some additional breakthrough or efforts such as important costs reduction for some technologies, very fast and extended deployment of infrastructures, major technological advances, strong societal changes, etc.

6.2.2 Disaggregation methodology per Member State

The disaggregation method is used, when levels are defined with EU level targets, mostly applied when a lever is described by specific units (i.e. value per reference value). These values then need to be disaggregated to country level targets.

No disaggregation method was applied in defining the different levels, as on one hand the levers are described by absolute, physical values (i.e. MWs of capacities) and the trajectories were drawn directly on Member State level considering current power generation mix, national policies, projections and features, as detailed at the description of each lever. This approach is justified by the article 194 of the Treaty on the Functioning of the European Union stating that it is a *Member State's right to determine the conditions for exploiting its energy resources, its choice between different energy sources and the general structure of its energy supply (European Union, 2008)*.

6.2.3 Curve shapes

While the levers describing the spread of renewable based power generation technologies have trajectories described by mathematical formulation, the levers of fossil-fuel and nuclear based power generation are defined manually in a bottom-up approach.

In the module, a linear shape for the trajectories of renewable based power generation between 2020 and 2050 is assumed. Between the base year (2015) and 2020, there are no trajectories set but based on actual statistical value a most likely figure is extrapolated; same for all ambition levels. The 2050 end point depends on the final ambition (i.e. the capacity values in 2050) value. Exception is the marine power, where industry projections (not described by equations) were extrapolated.

The future development of a country's coal based, and nuclear power plant stock is defined by investigating the future of each power plant of that type (bottom-up method) with considering the national phase-out policies and timing. That means that the starting value for 2015 is the actual generation capacity in a country, which consists of several power plants. Between the base year (2015) and 2020, there are no trajectories set but based on actual power plant stock and announced retirements and/or new-builts a most likely figure is extrapolated for 2020; same for all ambition levels. For years after 2020, for each power plant, one or more potential closure dates are defined in different databases (for exact referencing, please see the section about levers), meaning, that in the year of the closure the total capacity will be lowered by the capacity of that plant. Depending on the timing for closure for each power plant included in the mix, as well as the commission timeline for potential new power plants, the trajectories follow different shapes. The 2050 value depends on the actual policies of the country and the conditions for the power plant stock in 2015 and 2020. As a result, the trajectories develop not continuously but rather step-by-step, where the size of each step is defined by the capacity of the power plants closed/installed in each period. Considering this bottom-up approach, the trajectories cannot be described by mathematical equation.

For the decommissioning of existing natural gas and oil-based power generation capacities (as part of the fossil fuel phase-out lever), the method by Farfan and Breyer (2017) was used, as described in a previous chapter.

6.3 Lever specification

6.3.1 Wind power generation capacity additions

6.3.1.1 Lever description

With this lever, the user can set the amount of wind power generating capacities per country. The lever includes both on- and off-shore generation with the values displayed separately. Setting is only possible together (on- and off-shore) through the four levels of wind power generation to allow easier operation and respecting the limited number of levers.

6.3.1.2 Rationale for lever and level choices

Wind power generation can be a cornerstone of a decarbonized electricity system in many EU countries (Hübler and Löschel, 2013). With setting the levels, the user can choose the amount of wind power capacities in the electricity production mix influencing the production and emissions of the sector.

<u>Current situation</u>

Based on the data of Wind Europe (former EWEA), the wind power industry association, in 2015, a wind power capacity of 142 GW was operational in the EU: 131 GW onshore and 11 GW offshore. In that year, wind energy overtook hydropower as the third largest source of power generation in the EU with a 15.6% share of total power capacity. The EU total installed power capacity increased by 11 GW net in 2015 to 908 GW. Wind power accounts for one third of all new power installations since 2000 in the EU (EWEA, 2016a). Due to the continuous increase of wind power capacities, with a total net installed capacity of 169 GW in 2017, wind energy is the second largest form of power generation capacity in Europe, closely approaching natural gas installations (Wind Europe, 2017), see Figure 18 and Figure 19. Most of the installations are onshore but with increasing fraction of offshore wind power capacities.

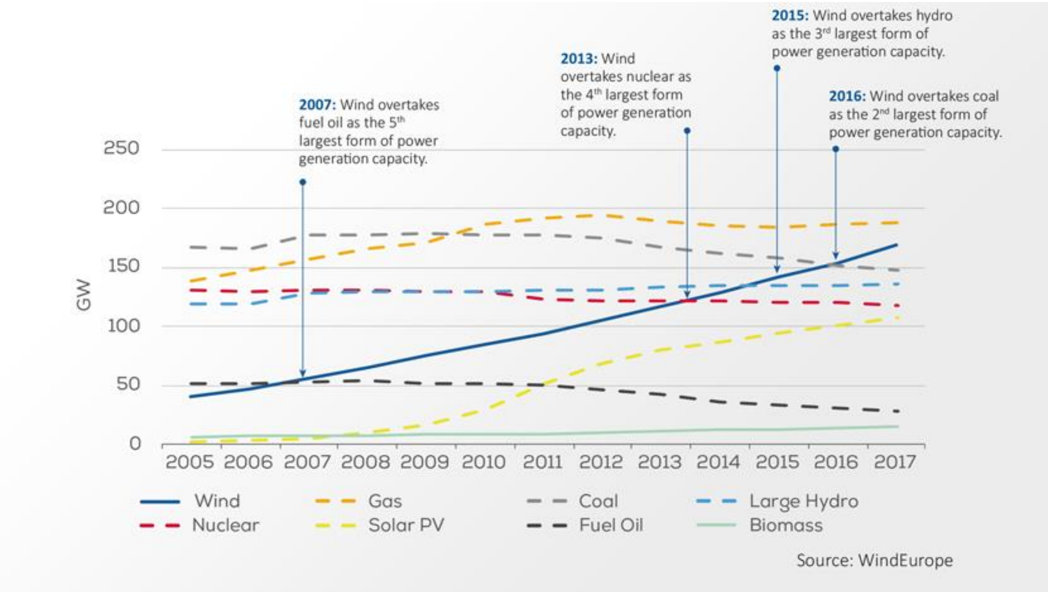

Figure 18 – Total power generation capacity in the European Union 2005-2017

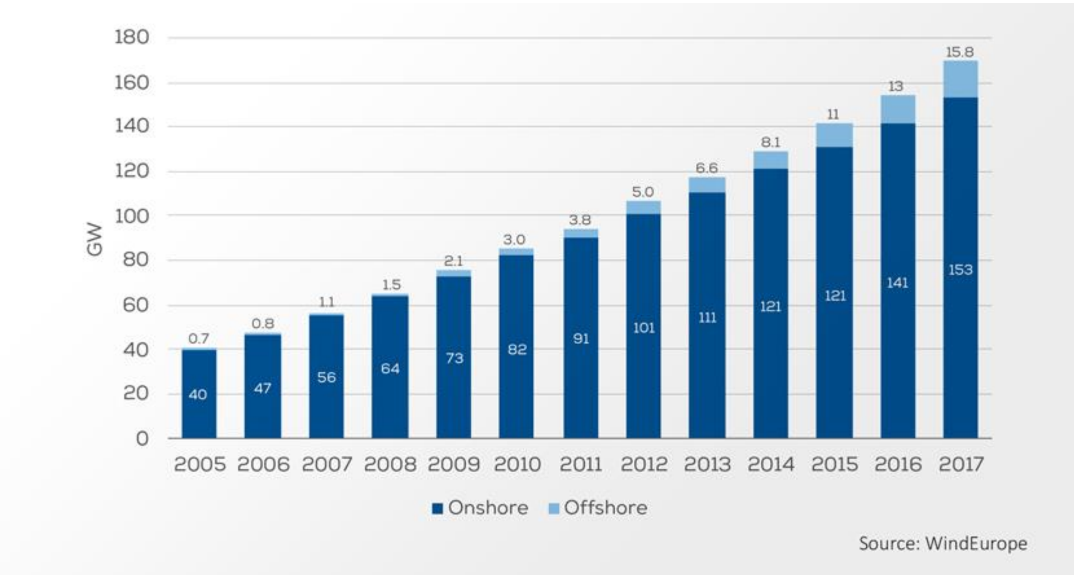

Figure 19 – Cumulative installations onshore and offshore in the EU

Regarding country level breakdown, in 2015 Germany was the EU country with the largest installed capacity (45 GW), followed by Spain (23 GW), the UK (14 GW) and France (10 GW). In 16 EU countries more than 1 GW wind power capacity is installed, nine of these have more than 5 GW, for more details see Figure 20. The total wind power capacity installed at the end of 2015 could produce 315 TWh and cover 11.4% of the EU electricity consumption in a normal wind year (EWEA, 2016a).

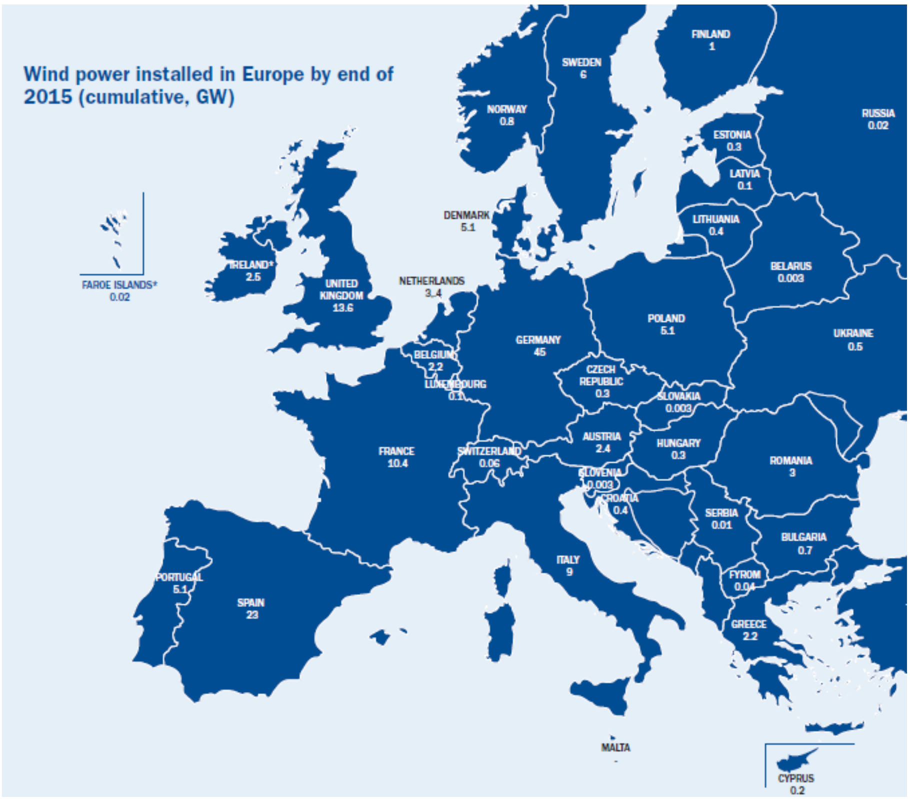

Figure 20 – Wind power in Europe by end of 2015 (cumulative, GW), source: EWEA, 2016a

<u>Various scenarios for 2050</u>

Different scenarios are available to project the further spread of wind power capacities in Europe. Apart from projections of Wind Europe, energy system modelling tools have trajectories for wind power, as being an important part of the future energy system.

In its 2030 outlook, Wind Europe developed three scenarios with separate values for on- and off-shore power generation and compared them with other projections (see Figure 21). While the ranges of installed capacity vary on a broad scale, all the projections describe linear trajectories. This curve shape is also applied for the future trend of wind power in this study.

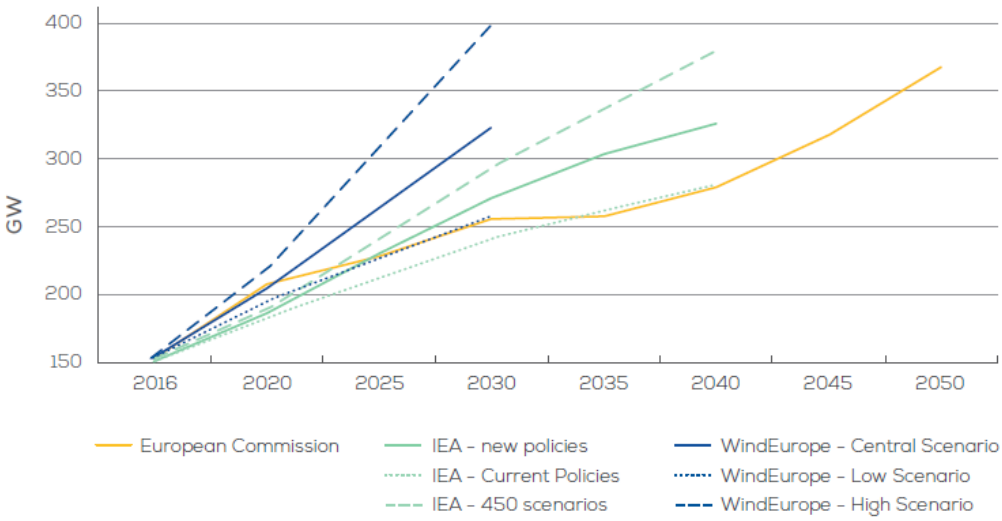

Figure 21 - Comparison of different scenarios for cumulative wind power capacity in the EU, source: Nighiem et al., 2017

According to scenarios from different sources, the European total onshore wind power capacity in 2050 can be in the range of 245-875 GW, while off-shore lies between 190-373 GW (Zappa et al., 2019), depending mainly on policies.

The EU Reference Scenario 2016 predicts 367.6 GW of total wind power capacities in EU-28 for 2050, which was also our starting point for the definition of the lowest level in the ambition setting of EUCalc. This is due to the reason, that the Reference Scenario provides a benchmark, which can be used for comparing new policy proposals and allows policymakers to analyse the long-term economic, energy, climate and transport outlook based on the current policy framework (European Commission, 2019).

Disaggregation methodology rational

No disaggregation was applied. Trajectories were defined directly on country level.

Feedback from the stakeholder consultations

In general, stakeholders consulted during the co-design workshop agreed with the set of levers proposed. During the stakeholder workshop, differentiation of on- and off-shore values was suggested and included into trajectory definitions. Concrete values, as presented above, were not available at the time of the workshop, thus will be consulted during the call for evidence process.

6.3.1.3 Ambition levels & disaggregation method

The level trajectories were defined using the below sources as starting points; however, they were adjusted by considering the maximal values of electricity demand in 2050 in order to prevent oversupply and stranded assets. The comparison to the maximal electricity demand was carried out on trading zone level[4] in order to account for export-import possibilities in balancing.

For Level 4, the starting data was the potential estimation by Scholz (2012), which is based on detailed assessment of potentials considering geographical constraints and technology development, as detailed in the resource work. In this reference, German and Belgian data were not accurate to calculate off-shore wind power potential. Therefore, the 'Technical report on Member State results of the EUCO policy scenarios' (E3MLab & IIASA, 2016) data was used for Germany and Belgium as starting points. After 2030, the Microsoft Excel forecast function was used to determine the values between 2035-2050. For each analysed year, the entire previous period was considered.

The 2050 value of the Level 1 trajectories of both on- and off-shore are adjusted by the same extent as the potential figures for Level 4.

The less ambitious Level 1 is based on the EU Reference Scenario 2016 (Capros et al., 2016) except for Switzerland. Due to the lack of a reference scenario for Switzerland, the next two points of the Level 1 trajectory were selected and connected with linear extrapolation. For the 2020 starting value the installed wind power capacity in 2015 by the Swiss Federal Office of Energy was extrapolated (Kaufmann, 2016). For 2050 the value for 2040 of the 'ENTSO Scenario 2018 Generation Capacities' Scenario 2040 GCA[5] was extrapolated.

[4] for trading zone definition please see deliverable 8.5 "Storage requirements module"

[5] https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/Scenarios%20Data%20Sets/ENTSO%20Scenario%202018%20Generation%20Capacities.xlsm

As the above sources do not contain scenarios separately for on- and off-shore wind, the figures were considered as total and broken down to on- and off-shore based on the next calculations for the relevant countries. In order to calculate the 2030 ratio, the data from 'Wind energy in Europe: Scenarios for 2030' (Nighiem et al., 2017) were used. Between 2020 and 2025, the average of the values from 2017 and 2030 were used. After 2030, rates of 2030 were applied.

Table 8 summarizes the figures obtained as described above. Linear interpolation was used for calculating Level 2 and 3 (i.e. for Level 2, the 2050 value is Level 1 plus one third of the difference between Level 1 and 4, while Level 3 is two-third of the difference). Values for 2020 are the same for each level and reflect a most likely value based on the actual statistical figures. In some cases, the observed statistical trend between 2015-2017 and 2012-2017 showed already more ambitious target and achievement than reference scenario for 2050, therefore in those cases the 2050 value for the reference scenario was overwritten. From 2020 to 2050, linear interpolation was applied in case of each level trajectories.

Table 8 – Summary of the wind power capacities levels

Country	On-shore wind power capacities, GW				Off-shore wind power capacities, GW			
	2015	2020	2050 L1	2050 L4	2015	2020	2050 L1	2050 L4
Austria	2.5	2.7	6.8	15.0	0.0	0.0	0.0	0.0
Belgium	1.5	2.5	5.4	6.1	0.7	1.2	3.9	5.6
Bulgaria	0.7	1.7	2.3	8.4	0.0	0.0	0.0	6.3
Croatia	0.4	0.8	0.9	3.1	0.0	0.0	0.0	6.6
Cyprus	0.2	0.2	0.3	0.8	0.0	0.0	0.0	0.5
Czech Republic	0.3	0.4	0.8	14.0	0.0	0.0	0.0	0.0
Denmark	3.8	4.8	5.0	6.2	1.3	1.4	1.8	17.0
Estonia	0.3	0.8	0.9	1.4	0.0	0.0	0.5	3.9
Finland	1.0	3.5	4.2	22.6	0.0	0.3	1.3	31.2
France	10.2	18.2	43.1	89.7	0.0	0.0	5.2	203.5
Germany	41.3	64.3	70.6	90.5	3.3	8.3	16.1	72.0
Greece	2.1	3.4	3.7	9.6	0.0	0.0	0.0	25.8
Hungary	0.3	0.3	1.0	10.6	0.0	0.0	0.0	0.0
Ireland	2.4	4.7	4.9	6.4	0.0	0.0	0.5	13.5
Italy	9.1	10.6	21.5	47.3	0.0	0.0	0.0	121.4
Latvia	0.1	0.1	0.2	1.4	0.0	0.0	0.0	3.6
Lithuania	0.4	0.7	0.7	2.4	0.0	0.0	0.0	3.4
Luxembourg	0.1	0.3	0.5	0.3	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.6
Netherlands	3.0	3.5	4.9	8.0	0.4	1.9	3.6	81.6
Poland	4.9	7.9	13.5	46.7	0.0	0.0	2.2	38.7
Portugal	4.9	5.4	5.6	8.3	0.0	0.0	0.0	7.6
Romania	3.2	3.2	4.4	15.6	0.0	0.0	0.0	6.9
Slovakia	0.0	0.0	0.2	8.4	0.0	0.0	0.0	0.0
Slovenia	0.0	0.0	0.1	3.8	0.0	0.0	0.0	6.3
Spain	23.0	23.5	29.5	52.2	0.0	0.0	0.0	28.1
Sweden	5.6	8.1	8.6	26.5	0.2	0.0	0.0	55.0
Switzerland	0.1	0.6	2.5	6.0	0.0	0.0	0.0	0.0
UK	9.3	18.3	21.3	27.3	5.1	10.1	13.1	154.0
EU28+CH total	**130.6**	**191.3**	**266.5**	**535.4**	**11.0**	**23.4**	**48.3**	**893.9**

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6.3.2 Solar power generation capacity additions

6.3.2.1 Lever description

With this lever, the user can set the amount of solar power generating capacities per country. The lever includes both PV and CSP generation with the values displayed separately. Setting is only possible together through the four levels of solar power generation to allow easier operation and respect the limited number of levers.

6.3.2.2 Rationale for lever and level choices

Solar power generation can be a cornerstone of a decarbonized electricity system in many EU countries (Hübler and Löschel, 2013). With setting the levels, the user can choose the amount of solar power capacities in the electricity production mix influencing the production and emissions of the sector.

Current situation

Next to wind power, PV capacities are adding to the European power plant stock in the second largest pace. Since 2005, solar PV electricity generation capacity has increased from 1.9 GW to 102 GW at the end of 2016 (Figure 22). Already in 2014, the 2020 National Renewable Energy Action Plan (NREAP) target of 83.7 GW was exceeded, reaching about 88.4 GW (Jager-Waldau, 2017). The distribution of installed capacities is very uneven between the Member States. Only two countries, Germany and Italy installed more than half of the total European PV power plant stock, followed by UK and France.

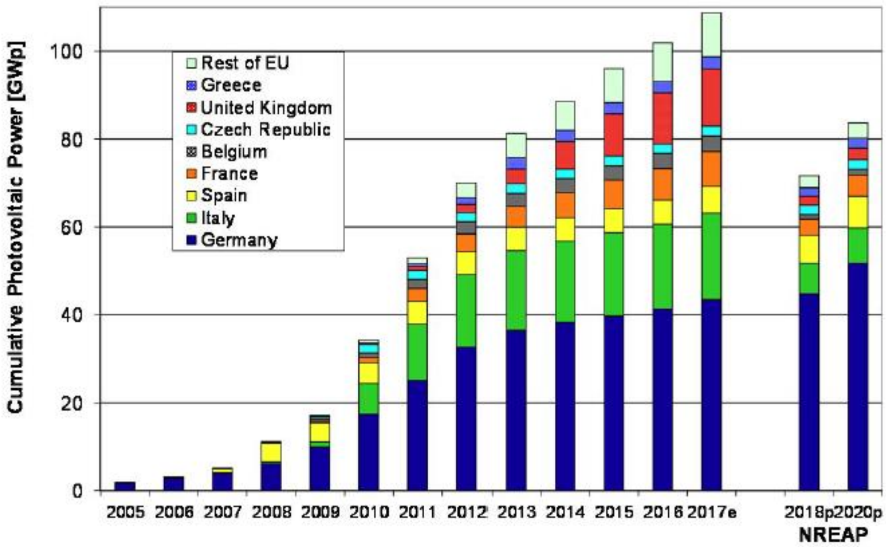


Figure 22 – Cumulative installed grid-connected PV capacity in EU plus candidate countries compared with the NREAP target for 2020, source: Jager-Waldau, 2017

While the cumulative capacity has been growing, it must be noted that the annually installed capacities decreased from 2011 until 2016 (Figure 23). This is due to the not properly designed support schemes with slow reaction to the very rapidly growing market and this led to unsustainable local market growth rates. To counteract this, unpredictable and frequent changes in the support schemes, as well as legal requirements, led to installation peaks before the announced deadlines and high uncertainty for potential investors (Jager-Waldau, 2017).

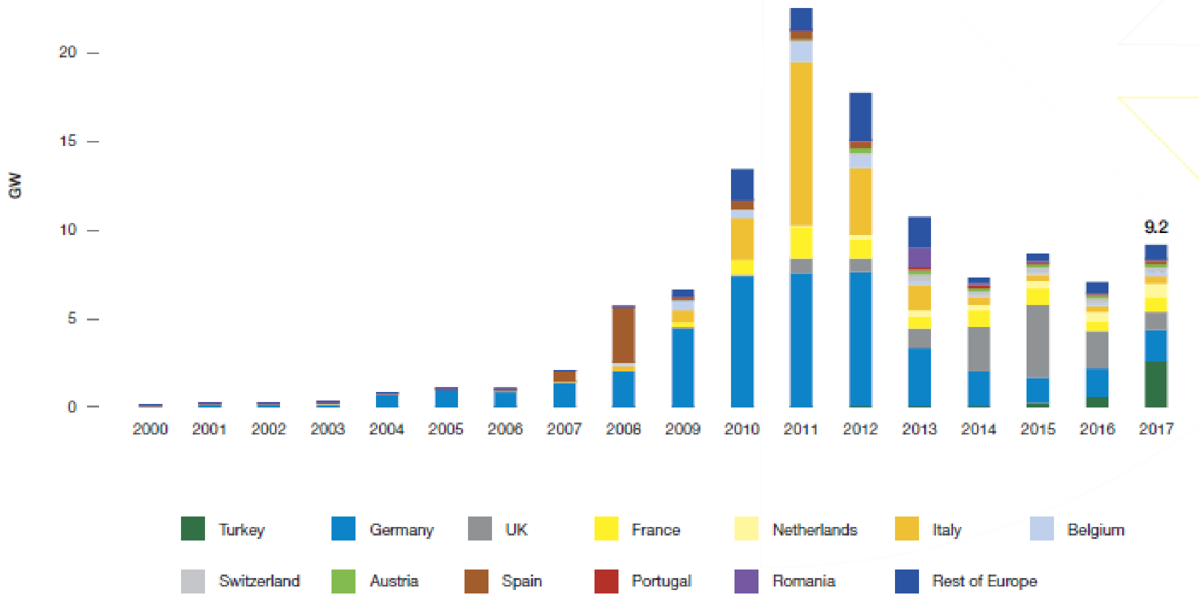


Figure 23 – European solar PV annual grid connections 2000-2017, source: SolarPowerEurope, 2018

In 2015, UK added the most PV capacities with 4.2 GW within a year. However, the government cancelled its solar support in 2016, which led to a steep downhill trip with only 954 MW installed in 2017, a decrease of over 50% from 2.1 GW in 2016, which is half of the figure of 2015 [31]. The example of this one country already shows the sensitivity of the PV market to policy changes. Annual installations in Germany were second with 1.45 GW in 2015, followed by 1.52 GW and 1.8 GW, in 2016 and 2017, respectively (SolarPowerEurope, 2018).

CSP technology is present with low capacities in Europe, in 2015 installed CSP capacity was 2.3 GW (Figure 24) with the bulk of those coming from Spain, only a few pilots in Italy (7,5 MW), France (0.75 MW) and Germany (1.5 MW) (EurObserv'ER, 2017).

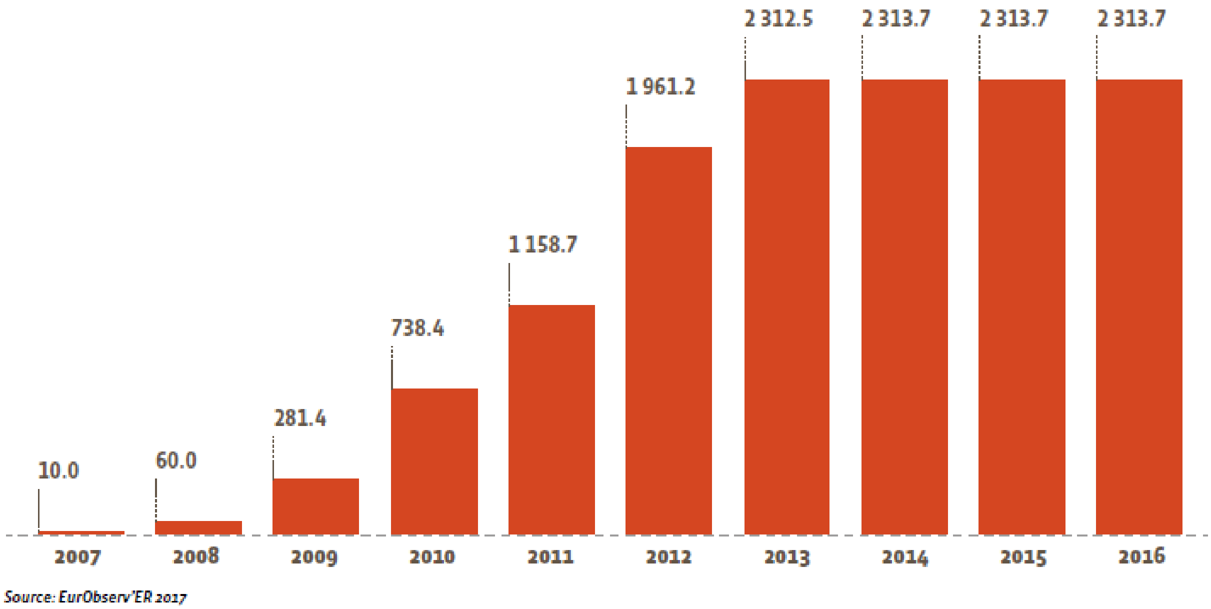


Figure 24 - European Union concentrated solar power capacity trend (MWe), source: EurObserv'ER, 2017

Various scenarios for 2050

According to projections, solar PV can become dominant in the European power generation fleet. Bloomberg NEF believes it could account for a 36% share or 1 400 GW, while according to Prof. Christian Breyer of Lappeenranta University of Technology solar power technologies will provide nearly 2 TW of power generation in Europe, of which nearly 700 GW will be utility-scale and nearly 1.3 TW rooftop solar PV (BNEF, 2018b). For 2050, other sources indicate that the European PV capacity can be in the range of 603-962 GW (Zappa et al., 2019).

The EU Reference Scenario 2016 predicts 294.7 GW of PV capacity in EU-28 for 2050, which was also our starting point for the definition of the lowest level in the ambition setting of EUCalc. This is due to the reason that the Reference Scenario provides a benchmark, which can be used for comparing new policy proposals and allows policymakers to analyse the long-term economic, energy, climate and transport outlook based on the current policy framework (European Commission, 2019).

Disaggregation methodology rational

No disaggregation was applied. Trajectories were defined directly on country level.

Feedback from the stakeholder consultations

In general, stakeholders consulted during the co-design workshop agreed with the set of levers proposed. Concrete values, as presented above, were not available at the time of the workshop, thus will be consulted during the call for evidence process.

6.3.2.3 Ambition levels & disaggregation method

The level trajectories were defined using the below sources as starting points; however, they were adjusted by considering the maximal values of electricity demand in 2050 in order to prevent oversupply and stranded assets. The comparison to the maximal electricity demand was carried out on trading zone level[6] in order to account for export-import possibilities in balancing.

For both technologies, the starting data for the most ambitious Level 4 was the potential estimation by Scholz (2012), which is based on detailed assessment of potentials considering geographical constrains and technology development, as detailed in the resource work. For Italy, the upper limit capacity was chosen as defined in the 'Technical report on Member State results of the EUCO policy scenarios' (E3MLab & IIASA, 2016) data. The adjustment of these trajectories for the maximal electricity demand means that the potential is exploited in different extent by country by 2050. Therefore, in case of level 4 the potential figures mean a ceiling for 2050 that cannot be exceeded.

The 2050 value of the Level 1 trajectories of both technologies are adjusted by the same extent as the potential figures for Level 4.

For PV, the less ambitious Level 1 is based on the EU Reference Scenario 2016 (Capros et al., 2016) except for Switzerland. Due to the lack of a reference scenario for Switzerland, the two points of the Level 1 trajectory were selected and connected with linear interpolation. For the 2020 starting value the installed PV power capacity in 2015 by the Swiss Federal Office of Energy was extrapolated

[6] for trading zone definition please see deliverable 8.5 "Storage requirements module"

(Kaufmann, 2016). For 2050 the value for 2040 of the 'ENTSO Scenario 2018 Generation Capacities' Scenario 2040 GCA[7] was extrapolated.

For CSP, the 2020 and 2050 starting values of the Level 1 trajectory were selected and connected with linear extrapolation. For 2015, historical values as reported in the JRC IDEES database (Mantzos et al., 2018) were used. For 2050 the 'ENTSO Scenario 2018 Generation Capacities' Scenario 2040 DG [8] was used with extrapolation to 2050.

Table 9 summarizes the figures obtained as described above. Linear interpolation was used for calculating Levels 2 and 3 (i.e. for Level 2, the 2050 value is Level 1 plus one third of the difference between Level 1 and 4, while Level 3 is at two-third of the difference). Values for 2020 are the same for each level and reflect a most likely value based on the actual statistical figures. In some cases, the observed statistical trend between 2015-2017 and 2012-2017 showed already more ambitious target and achievement than reference scenario for 2050, therefore in those cases the 2050 value for the reference scenario was overwritten. From 2020 to 2050, linear interpolation was applied in case of each level trajectories.

Though not present directly in the level, the share of rooftop PV is also expressed to account for the different costs in the calculation. For this reason, the share of rooftop PV is fixed at 5.8% of the capacities as shown in Table 9. This ratio is based on the figures of Solar Power Europe forecasting the world total solar PV market and the rooftop market to for 2022. The figure shows the average value of the rooftop share in the minimum and maximum scenarios of Solar Power Europe (2018).

7 https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/Scenarios%20Data%20Sets/ENTSO%20Scenario%202018%20Generation%20Capacities.xlsm

8 https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/Scenarios%20Data%20Sets/ENTSO%20Scenario%202018%20Generation%20Capacities.xlsm

Table 9 – Summary of the solar power capacities levels

Country	PV capacities, GW				CSP capacities. GW			
	2015	2020	2050 L1	2050 L4	2015	2020	2050 L1	2050 L4
Austria	0.9	1.8	4.0	13.0	0.0	0.0	0.0	0.0
Belgium	3.1	4.1	5.1	23.0	0.0	0.0	0.0	0.0
Bulgaria	1.0	1.0	2.0	7.6	0.0	0.0	0.0	0.0
Croatia	0.0	0.1	0.3	0.9	0.0	0.0	0.0	0.0
Cyprus	0.1	0.2	0.3	2.2	0.0	0.0	<0.1	1.5
Czech Republic	2.1	2.1	3.1	18.0	0.0	0.0	0.0	0.0
Denmark	0.8	1.0	1.1	2.0	0.0	0.0	0.0	0.0
Estonia	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0
Finland	0.0	0.2	0.2	4.1	0.0	0.0	0.0	0.0
France	6.8	12.3	36.9	81.0	0.0	0.0	0.0	5.5
Germany	39.2	46.2	86.1	108.0	0.0	0.0	0.0	0.0
Greece	2.6	2.6	4.3	5.8	0.0	0.0	0.1	4.2
Hungary	0.2	0.7	1.0	11.2	0.0	0.0	0.0	0.0
Ireland	0.0	0.1	0.1	0.3	0.0	0.0	0.0	0.0
Italy	18.9	21.4	46.8	68.9	0.0	0.0	0.2	28.0
Latvia	0.0	0.1	0.1	0.5	0.0	0.0	0.0	0.0
Lithuania	0.1	0.1	0.4	1.1	0.0	0.0	0.0	0.0
Luxembourg	0.1	0.2	0.2	0.7	0.0	0.0	0.0	0.0
Malta	0.1	0.1	0.1	0.2	0.0	0.0	<0.1	<0.1
Netherlands	1.5	5.0	5.4	14.4	0.0	0.0	0.0	0.0
Poland	0.1	0.6	4.0	31.7	0.0	0.0	0.0	0.0
Portugal	0.4	0.8	1.0	2.9	0.0	0.0	0.0	23.9
Romania	1.3	1.5	2.1	16.4	0.0	0.0	0.0	0.0
Slovakia	0.5	0.5	1.1	10.2	0.0	0.0	0.0	0.0
Slovenia	0.2	0.2	0.5	1.4	0.0	0.0	0.0	0.0
Spain	4.9	5.0	16.9	24.1	2.3	2.3	2.6	125.6
Sweden	0.1	0.5	0.6	4.8	0.0	0.0	0.0	0.0
Switzerland	0.4	0.7	2.6	19.3	0.0	0.0	0.0	0.0
UK	9.5	14.5	15.5	20.0	0.0	0.0	0.0	0.0
EU28+CH total	**95.1**	**123.5**	**242.7**	**494.1**	**2.3**	**2.3**	**3.0**	**188.8**

6.3.3 Changes in nuclear power generation capacities

6.3.3.1 Lever description

With this lever, the user can set the future development of the base year nuclear power generation capacity per country. The options included in the levels depend on the policies of the countries towards nuclear energy – it can be phase-out, maintenance or even expansion of nuclear power capacities. The setting of the levels offers a possibility for users to investigate the impact of different timings.

6.3.3.2 Rationale for lever and level choices

Nuclear power generation can significantly contribute to decarbonisation, offering emission free baseload power. However, due to different concerns and life cycle considerations, some countries decided not to use it or phase-out existing capacities. With setting the levels, the user can choose the future of the base year nuclear generation capacities depending on the policy of the country. The impact of timing on phase-out and expansion can be investigated on pathways.

Current situation

According to the World Nuclear Industry Status Report, in 2015 128 reactors were in operation in the EU, of which almost half (58) were in France. Total, these 128 reactors have a capacity of 119.7 GW (Schneider et al., 2015), Figure 25.

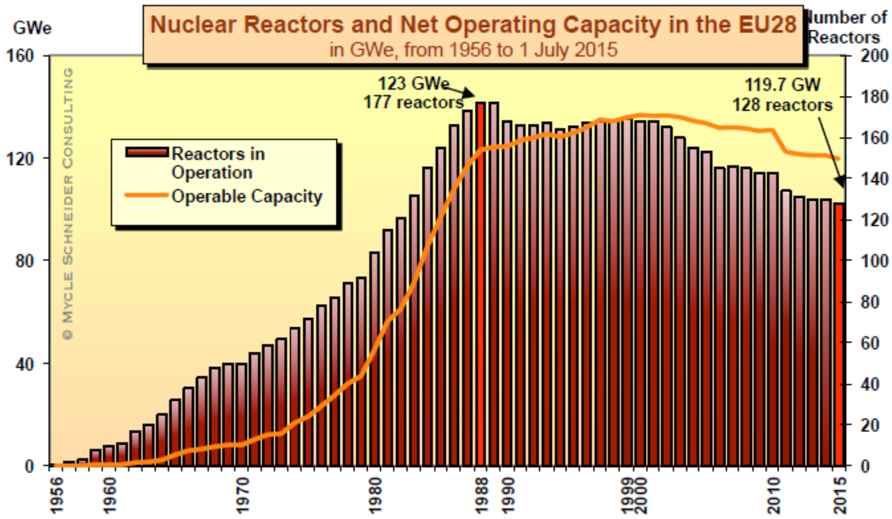


Figure 25 - Nuclear Reactors and Net Operating Capacity in the EU28, source: Schneider et al., 2015

The number of reactors in operation has been decreasing since 1989 in the EU, whereas the vast majority of the facilities, 109 units or 85%, are located in eight of the western countries, and only 19 are in the six newer member states using nuclear power (Schneider et al., 2015). See Figure 26 for countries with nuclear power plants.

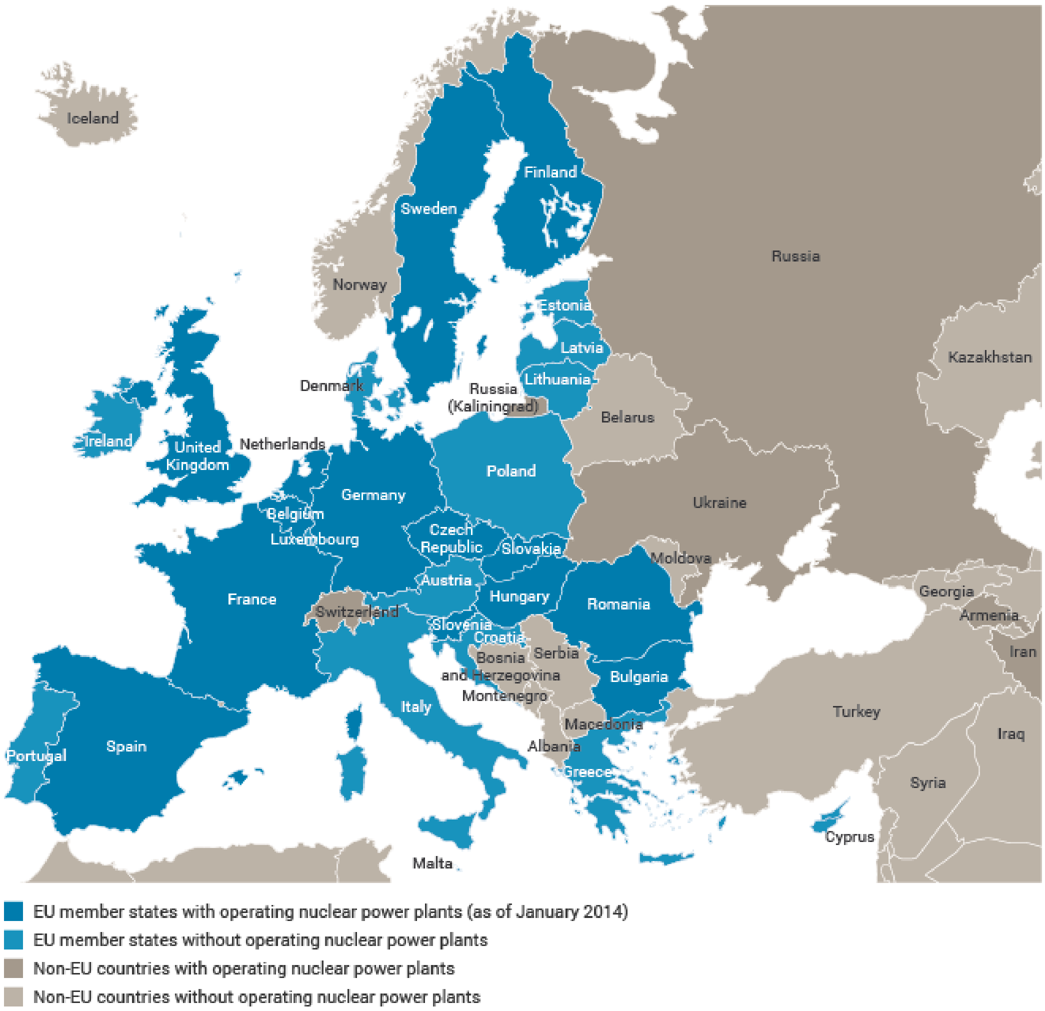


Figure 26 – Nuclear power in EU, January 2014, source: WNA, 2018

The currently operating reactors were built in three nuclear construction waves: two small ones in the 1960s and the 1970s and a larger one in the 1980s (mainly in France), see Figure 27. As currently there is no new-build program (latest start-up of a single reactor was in 2007), the average age of nuclear power plants is increasing continuously and at mid-2015 stood at 30.6 years. The age distribution shows that now over half (71 out of the 128) of the EU's nuclear reactors have been in operation for over 31 years (Schneider et al., 2015). Meanwhile, due to changing policies, phasing-out and decommission of nuclear power plants have been taking place that led to a decreasing number of reactors in Europe.

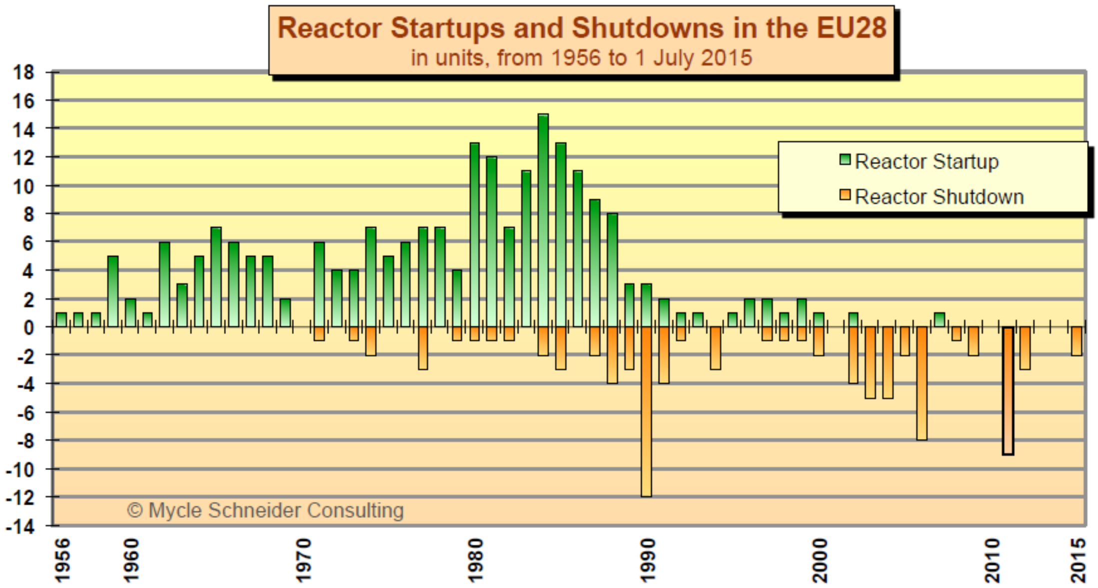


Figure 27 - Nuclear Reactors Startups and Shutdowns in the EU28, 1956–2015

<u>Various scenarios for 2050</u>

Nuclear energy is a controversial source of electricity, as the large-scale decarbonisation potential is coupled with concerns of operational safety and waste management. Due to ageing and phase-out policies, nuclear power generation is foreseen to decrease further in the EU, though Member States have different policies and plans with nuclear power, as indicated in annex.

On EU level, the IAEA projects that almost all of the existing nuclear power reactors in the combined regions of Northern, Western and Southern Europe are scheduled to be retired by 2050. In the low case, about 52 GW of nuclear capacity will be retired by 2030 and an additional 47 GW of capacity will be retired between 2030 and 2050. The projected additions of nuclear capacity in this case are only 8 GW by 2030 and some 16 GW by 2050. In the high case, nuclear power reactor retirements will be delayed; most of the reactors will be retired between 2030 and 2050. The additions of nuclear capacity in this case are projected to be 9 GW by 2030 and some 50 GW by 2050 (IAEA, 2018), Figure 28.

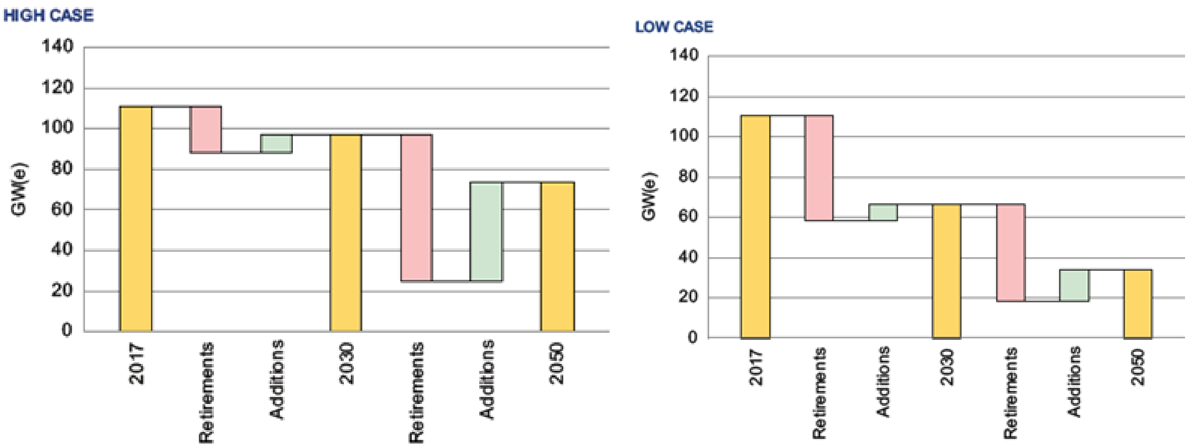


Figure 28 – Nuclear capacity in the combined regions of Northern, Western and Southern Europe: actual, retirements and additions, source: IAEA, 2018

Additionally, most of the deep decarbonisation scenarios aim for 100% renewables for 2050, thus they do not consider nuclear as part of the electricity generation mix (Zappa et al., 2019).

Disaggregation methodology rational

No disaggregation was applied. Trajectories were defined directly on country level.

Feedback from the stakeholder consultations

In general, stakeholders consulted during the co-design workshop agreed with the set of levers proposed. Concrete values, as presented above, were not available at the time of the workshop, thus will be consulted during the call for evidence process.

6.3.3.3 Ambition levels & disaggregation method

For nuclear power generation capacities, the country profiles of World Nuclear Association (WNA, 2019) are used considering also phase-out policies and intentions for new builds. A bottom-up method was used to create the level trajectories, described in more detail in the appendix, whereas Table 10 contains the 2050 values for each country. While for 2050 the value for the two levels can be the same, it does not mean necessarily the same trajectories leading there. Database of operating (as of 2015) nuclear power plants was built for every country. Between the base year (2015) and 2020, there are no trajectories set but based on actual power plant stock and announced retirements and/or new-builts a most likely figure is extrapolated for 2020; same for all ambition levels. After 2020, depending on the available pieces of information on operating licences (using data of the World Nuclear Association) and country level policies, a shutdown year was defined for each power plant separately considering timing options. For new nuclear power plants, the starting date was the factor changing between the levels, in some cases even considering cancellation of proposed new builds depending on the uncertainty and maturity around investment wills.

Regardless the nuclear policies of countries, level 1 equals to the lowest capacities or the quickest phase-out/slowest expansion, while level 4 is the highest amount of nuclear as soon as possible – considering the decarbonisation potential of nuclear power. However, level 4 also predicts decreasing capacities of nuclear which is due to the phase-out policies, as well as the ageing power plant stock and lack of plans for building new nuclear power plants.

Table 10 – Summary of the nuclear power capacities levels

Country	Nuclear power capacities, GW			
	2015	2020	2050 L1	2050 L4
Austria	0.0	0.0	0.0	0.0
Belgium	6.2	6.2	0.0	0.0
Bulgaria	2.1	2.1	1.0	4.2
Croatia	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0
Czech Republic	4.6	4.6	0.0	6.0
Denmark	0.0	0.0	0.0	0.0
Estonia	0.0	0.0	0.0	1.0
Finland	2.8	4.4	1.6	2.8
France	65.9	67.7	1.8	44.0
Germany	11.4	10.0	0.0	0.0
Greece	0.0	0.0	0.0	0.0
Hungary	2.1	2.1	0.0	2.4
Ireland	0.0	0.0	0.0	0.0
Italy	0.0	0.0	0.0	0.0
Latvia	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	1.2
Luxembourg	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0
Netherlands	0.5	0.5	0.0	0.0
Poland	0.0	0.0	0.0	6.0
Portugal	0.0	0.0	0.0	0.0
Romania	1.5	1.5	0.8	2.5
Slovakia	2.1	2.1	0.0	4.5
Slovenia	0.7	0.7	0.0	1.1
Spain	7.7	7.7	0.0	0.0
Sweden	10.0	9.0	0.0	2.6
Switzerland	3.3	2.9	0.0	0.0
UK	10.2	10.2	6.1	22.0
EU28+CH total	**131.1**	**131.7**	**11.3**	**100.9**

6.3.4 Changes in coal power generation capacities

6.3.4.1 Lever description

With this lever, the user can set the future development of the base year coal power generation capacity per country. The coal power plant stock can lead to lock-in situations and blocking decarbonisation, recognizing that already many countries announced coal phase-out policies. The setting of the levels offers a possibility for users to investigate the impact of different timings for coal phase-out. Even though some countries plan to maintain coal power generation in long term, addition of new coal power plant is only included in the lowest ambition level, Level 1.

6.3.4.2 Rationale for lever and level choices

Coal power generation is responsible for the main part of emissions from the electricity generation sector; thus, intention and timing of phase-out are decisive in decarbonisation pathways. Already many countries decided to phase-out coal, as well as others are considering it. With setting the levels, the user can choose the future of the base year coal power generation capacities depending on the policy of the country. The impact of the timing of phase-out can be investigated on decarbonisation pathways.

Current situation

In 2015, there were 280 coal power stations (sites usually with multiple units) in the EU with a total of 162.7 GW installed capacity. The coal power stations in 2015 were situated in 22 Member States: Cyprus, Estonia, Latvia, Lithuania, Luxembourg and Malta did not have coal power station in 2015 (Greenpeace and CAN, 2015). Since then, in 2016 Belgium also closed its only coal power plant going also coal free. On the other hand, Germany and Poland alone account for nearly half of EU's installed capacity (51%) and more than half of yearly emissions (54%) of all coal-fired power plants (Climate Analytics, 2017) see Figure 29 for details.

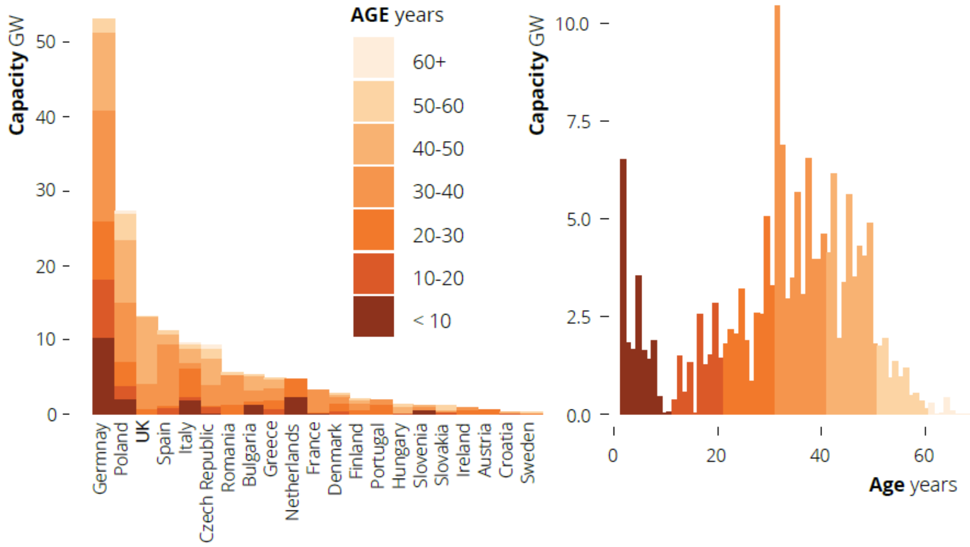


Figure 29 – Age structure and capacity by country (left panel) and total age structure (right panel) of the EU's coal power plant unit fleet, 2016, source: Climate Analytics, 2017

Two-third of the coal power fleet was 30 years old or even older in 2015. Comparatively little new capacity was installed during the 1990s and early 2000s but in the last decade, a considerable amount of new capacity has been built in Poland, the Netherlands, Italy and especially Germany. Unless these plants are retired before their lifetime, emissions will be locked longer, than what would be consistent with the EU's emissions reduction targets (Climate Analytics, 2017).

Nevertheless, due to ageing and decarbonisation actions, conventional power sources such as fuel oil and coal continued to decommission more capacity than they install. During 2015, the EU-28 shut down 8 GW of coal-based power generation while 4.7 GW were added (EWEA, 2016a). In 2016, again near 8 GW of coal-based power generation was decommissioned and less than 1 GW was installed (Jager-Waldau, 2017). However, the rate of decommissioning is slower than urgency of climate actions would require, thus phase-out plans are an essential part of decarbonisation in due time (Greenpeace and CAN, 2015).

Various scenarios for 2050

National coal phase-out plans are decisive in the future scenarios of coal-based power generation on country level. Climate Analytics compared closure scenarios needed to meet climate objectives with actual closure rates and retirement of existing plants. The analysis shows that even with no new coal power plants installed, cumulative CO_2 emissions from current coal-based electricity generation capacity would exceed both the Cancun Agreements and the Paris Agreement compatible cost-optimal emissions budgets (Climate Analytics, 2017), Figure 30.

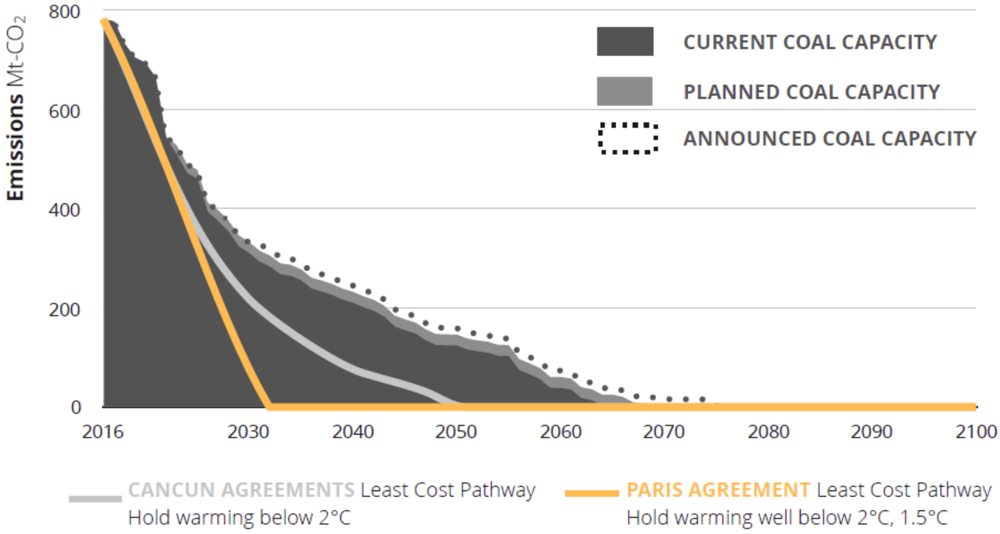


Figure 30 – European Union potential CO_2 emissions from existing and planned coal capacity against least-cost pathways, source: Climate Analytics, 2017

In order to fulfil the climate objectives, Europe needs to phase-out coal power generation by 2030 or 2050, to meet 1.5°C or 2°C targets respectively. This process can be sped up by implementation of coal phase-out policies, which are already present in multiple countries of Europe, see Figure 31, for targets see annex. However, the picture is different in Western and Eastern Europe. Western Europe is accelerating its coal exit – action on climate change and air pollution combined action to specifically phase out coal-fired power generation, are all impacting coal demand. Along with the expansion of renewables, these policy efforts will eventually push coal out of the Western European power mix. By contrast, most countries in Eastern Europe have not announced phase-out policies and a handful of new coal power plants are under construction in Poland, Greece and in the Balkans. Some countries in Eastern Europe are among the few places, where lignite remains the cornerstone of the electricity system (IEA, 2018).

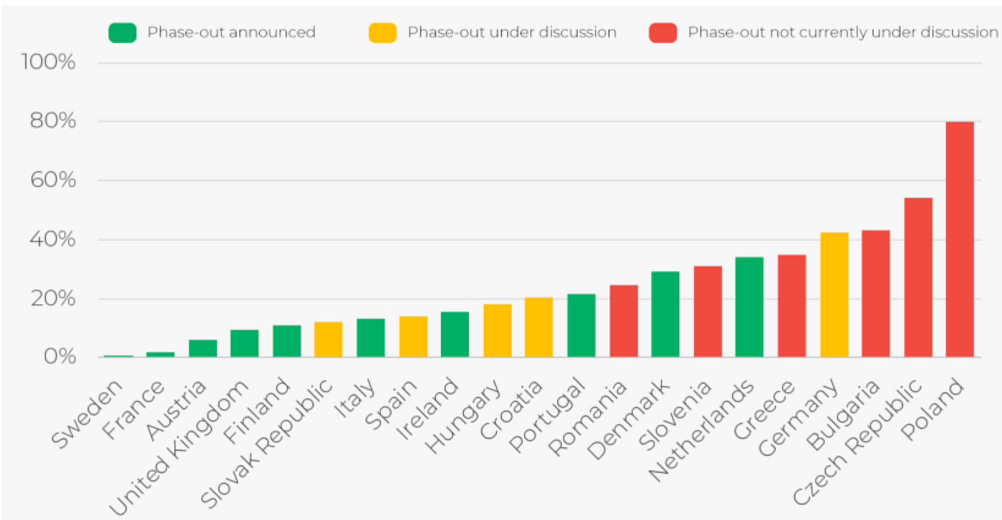


Figure 31 – Coal's share in power generation and phase-out policies, as of 2018, source: IEA, 2018

Considering the age of the coal power fleet, phase-out policies and climate objectives, there are scenarios projecting that Europe will have no coal power by 2050, while the EU Reference Scenario 2016 predicts 52 GW of coal (Zappa et al., 2019), which is less than one-third of the capacities of 2015.

Disaggregation methodology rational

No disaggregation was applied. Trajectories were defined directly on country level.

Feedback from the stakeholder consultations

In general, stakeholders consulted during the co-design workshop agreed with the set of levers proposed. Concrete values, as presented above, were not available at the time of the workshop, thus will be consulted during the call for evidence process.

6.3.4.3 Ambition levels & disaggregation method

A bottom-up method was used to create the level trajectories, see appendix for more details, whereas Table 11 contains the 2050 values for each country. While for 2050 the value for the two levels can be the same, it does not mean necessarily the same trajectories leading there.

Table 11 – Summary of the coal power capacities levels

Country	Coal power capacities, GW			
	2015	2020	2050 L1	2050 L4
Austria	1.4	0.2	0.0	0.0
Belgium	0.6	0.0	0.0	0.0
Bulgaria	5.2	5.2	1.3	0.0
Croatia	0.4	0.3	0.2	0.0
Cyprus	0.0	0.0	0.0	0.0
Czech Republic	9.7	9.7	1.9	0.0
Denmark	5.3	2.6	0.0	0.0
Estonia	2.1	2.1	2.1	0.0
Finland	4.7	2.0	0.0	0.0
France	4.6	4.6	0.2	0.0
Germany	59.6	56.2	14.3	0.0
Greece	4.0	4.0	1.3	0.0
Hungary	1.0	1.0	0.5	0.0
Ireland	1.2	1.2	0.0	0.0
Italy	6.3	6.1	1.0	0.0
Latvia	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0
Netherlands	5.1	4.1	2.8	0.0
Poland	29.3	28.5	13.9	0.0
Portugal	1.9	1.9	0.0	0.0
Romania	7.6	6.6	0.6	0.0
Slovakia	1.1	1.1	0.2	0.0
Slovenia	0.7	0.9	0.6	0.0
Spain	12.1	11.8	0.0	0.0
Sweden	0.3	0.3	0.0	0.0
Switzerland	0.0	0.0	0.0	0.0
UK	17.6	9.6	0.0	0.0
EU28+CH total	**181.8**	**160**	**40.9**	**0**

Database of operating (as of 2015) coal power plants was built for every country based on the Coal Map of Europe by CAN Europe (2015) and cross-checked and, if necessary, complemented by the databases of Climate Analytics (2019) and Global Coal Plant Tracker (2019). Between the base year (2015) and 2020, there are no trajectories set but based on actual power plant stock and announced retirements and/or new-builts a most likely figure is extrapolated for 2020; same for all ambition levels. After 2020, based on the Climate Analytics assessment (considering economic factors for phase-out), actual targets for phase-out and considering age of power plants, a shutdown year was defined for each power plant separately considering timing options. New coal power plants are allowed only at Level 1, intentions and plans to build new units were extracted from the Coal Map of Europe and the Global Coal Plant Tracker, including design and permit phase plants, too. Ambition levels mainly differ in the pace of phase-out, where Level 4 shows is a quick phase-out time before policy action, while for certain countries (such as Poland) Level 1 includes new coal-based capacities too.

6.3.5 Ratio of emissions from power plant and oil refinery sectors captured

6.3.5.1 Lever description

With this lever, the user can set the ratio of fossil fuel-based power plant and oil refinery stock equipped by carbon capture as a tool to reduce emissions. The amount of captured CO_2 is forwarded to the carbon capture, use and storage module. In that module the CO_2 is either sequestered or turned to synthetic natural gas based on modelling mechanisms and levers implemented in the module and described in the relevant documentation. In the energy supply module only the percentage of CO2 to be captured is controlled, but nothing else about destining the further fate of the captured emissions.

6.3.5.2 Rationale for lever and level choices

Carbon capture and storage (CCS) is a set of technologies aimed at capturing, transporting, and storing CO_2 emitted from power plants and industrial facilities. The goal of CCS is to prevent CO_2 from reaching the atmosphere by storing it in suitable underground geological formations. According to some scenarios with constant presence of fossil fuels in the power generation mix, CCS has importance in reaching climate objectives. However, with the growing share of renewables and policy intentions for quick phase-out of coal, these promises may not be valid.

<u>Current situation</u>

Following the European Council's 2007 decision to support up to 12 large-scale demonstration projects by 2015, the European Commission took a number of steps to establish a common regulatory and demonstration support framework. Despite these efforts, CCS has not yet taken off in Europe as initially envisaged. In turn, on 27 March 2013, the European Commission (EC) adopted a Consultative Communication on the future of CCS in Europe. The consultation found that at current low carbon prices, companies do not see an economic rationale to invest in CCS, however, the cost of CCS is expected to decrease in the long-run as a result of research and development activities, and the building of economies of scale (European Commission, 2013).

The Facilities Database of the Global CCS Institute (Global CCS Institute, 2019) lists and maps (Figure 32) a series of CCS projects in Europe with different scales, however, for some there is only outdated information available while others are discontinued. As of 2018, there are no existing, commercially viable uses of CCS projects in the EU. The only European country, where CCS is used on an industrial scale, is non-EU member Norway (EUobserver, 2018).

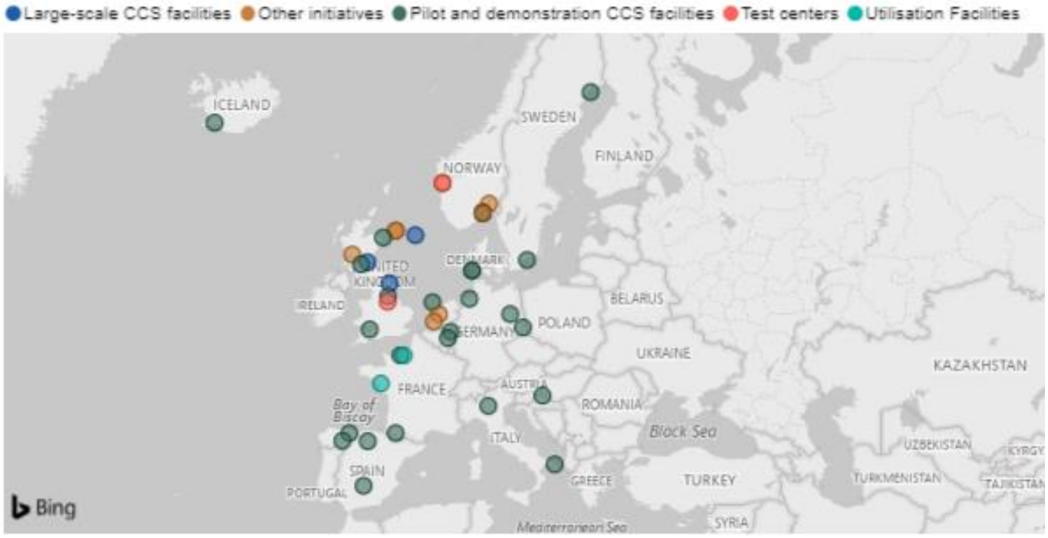


Figure 32 – Map of CCS projects in Europe, source: Global CCS Institute, Jan 2019

Various scenarios for 2050

A 2018 communication from the European Commission states that CCS was previously seen as a major decarbonisation option for the power sector but today this potential appears lower. However, CCS deployment is still necessary, especially in energy intensive industries and – in the transitional phase - for the production of carbon-free hydrogen. Thus, the main application area of CCS is not power generation anymore, due to phase-out plans (European Commission, 2018b).

Apart from further deployment needs, a limiting factor can be the geological potential and the abatement costs. CCS fuelled by lignite yields lower specific CO_2 abatement cost than CCS applied to hard coal and natural gas indicating early implementation of lignite CCS in countries currently having lignite as a fuel. As for geological limitations, not allowing onshore aquifer storage means that the application of capture receives a more profound role close to the North Sea (Odenberger et al., 2013). Implications of this can be seen on Figure 33.

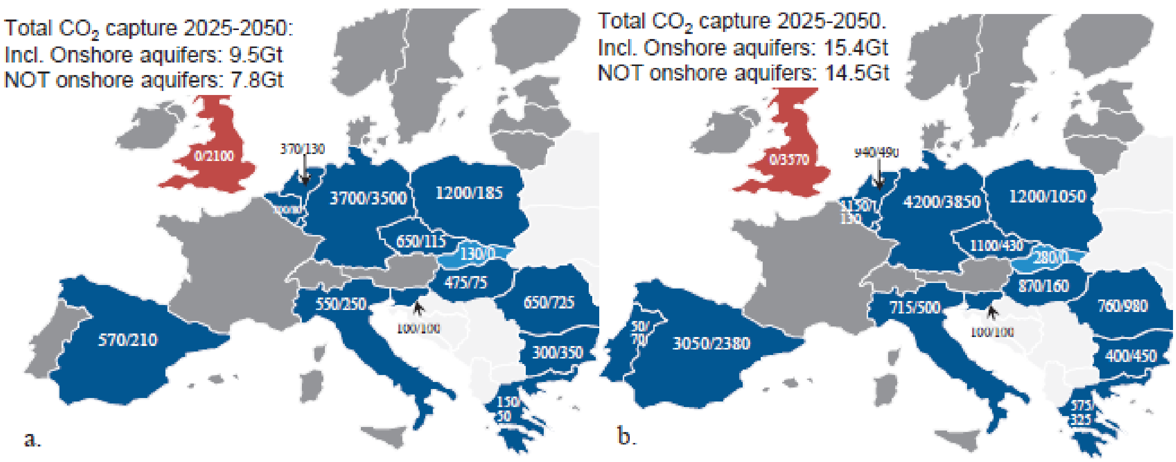


Figure 33 – Captured CO_2 between 2025 to 2050. Numbers give captured CO_2 in Mt for each Member State (first number from calculations including onshore aquifers/second number excluding onshore aquifers). Light blue for Slovakia indicates only application of CCS if onshore aquifers are allowed for storage, dark blue MSs indicate CCS application whether or not onshore aquifer storage is, source: Odenberger et al., 2013

Disaggregation methodology rational

No disaggregation was applied. Trajectories were defined directly on country level.

Feedback from the stakeholder consultations

In general, stakeholders consulted during the co-design workshop agreed with the set of levers proposed. Concrete values, as presented above, were not available at the time of the workshop, thus will be consulted during the call for evidence process.

6.3.5.3 Ambition levels & disaggregation method

The ambitions for carbon captured are expressed in form of ratios presented in Table 12 as percentage of captured emissions from fossil fuel-based power plants, biomass based technologies and oil refineries. The trajectories are based on the assumptions of Wildenborg et al. (2009) that the emission reduction target for CCS was set at 30% of the CO_2 emissions from power plants in Europe, which is to be achieved during the first half of this century. The paper shows that this target can be met, although major uncertainties remain in the timely availability of oil and gas fields and the storage potential of aquifers (Wildenborg et al., 2009). Based on level definition, this 30% was set as level 4 by 2050 and the other levels were defined compared to this objective. Even though, the emission base to which this percentages are refer can be influenced by setting of other levers (mainly the one about coal power plants) and is different in the original paper, we apply those percentages as fixed trajectories.

Table 12 – Percentage of CO_2 emissions captured in power generation and oil refinery sectors

Level	2015	2020	2025	2030	2035	2040	2045	2050
1	0%	0%	0%	0%	0%	0%	0%	0%
2	0%	0%	0%	0%	5%	10%	15%	20%
3	0%	0%	0%	5%	10%	15%	20%	25%
4	0%	0%	5%	10%	15%	20%	25%	30%

The above trajectories are applied for each country except for countries where the EU reference scenario assumes CCS in power generation. These countries, as shown in Table 13 are Bulgaria, Czech Republic, Denmark, France, Germany, Netherlands, Poland, Romania, Slovakia and United Kingdom (Capros et al., 2016). In these cases, the figures of the EU reference scenario are set as level 1 trajectory.

Table 13 – Ratio of CCS in the EU reference scenario applied as level 1, source: Capros et al., 2016

Country	2015	2020	2025	2030	2035	2040	2045	2050
Bulgaria	0%	0%	0%	0%	0%	0%	0%	6%
Czech Republic	0%	0%	0%	0%	0%	0%	0%	4%
Denmark	0%	0%	0%	0%	0%	0%	1%	1%
France	0%	0%	0%	0%	0%	0%	0%	<1%
Germany	0%	0%	0%	0%	0%	0%	0%	5%
Netherlands	0%	0%	1%	1%	1%	1%	1%	1%
Poland	0%	0%	0%	0%	0%	0%	6%	9%
Romania	0%	0%	0%	0%	0%	0%	0%	5%
Slovakia	0%	0%	0%	0%	0%	0%	0%	1%
United Kingdom	0%	1%	1%	1%	1%	1%	1%	1%

The figures in the above table were obtained by a transformation, as the indicator to describe the CCS in the reference scenario is not the same that we use. In our definition, the percentage applies to the emissions that is captured, while the reference scenario expresses it as percentage of electricity from CCS (where electricity is the total electricity generated). In order to transform it to a compatible unit, the percentage of electricity from CCS was multiplied with the (100 – percentage of carbon free (RES, nuclear) gross electricity generation), with both variables from Capros et al., 2016. Nevertheless, the base on we apply the percentage is subject to change depending on lever setting, as the installed capacities and production of emitting technologies can change.

In the view of ambitious and short-term coal phase-out policies of multiple countries, the perspectives of carbon capture become questionable in the power sector as the baseload nature of coal power plants and their scales could favour carbon capture. Investments are highly doubtful into technologies to be phased-out in less than 10 years.

6.3.6 Other renewables

6.3.6.1 Lever description

With this lever, the user can set the combined amount of marine, geothermal and hydropower generating capacities per country. The lever includes all these power generation capacities with the values displayed separately but setting is only possible together through the four levels. The rational of combining those technologies into one lever is that there is barely such a country, where all the three technologies can play significant roles at the same time, as spread is limited by geographical and geological conditions. Additional, hydropower generation potential is already well exploited, limiting the addition of more capacities. Under this lever, hydropower is only considered for primary production of electricity, storage units are included in the storage module.

6.3.6.2 Rationale for lever and level choices

With setting the levels, the user can choose what amount of combined marine, geothermal and hydropower capacities are in the electricity production mix influencing the production and emissions of the sector. New addition of those technologies can play a role in some of the countries, while complement decarbonization pathways in others.

Current situation

The reason of merging these three technologies into one lever can be captured well from Figure 34. Hydropower provides the largest source of renewable electricity production in the European Union (and thus capacities with wind closely approaching but far lower production due to lower capacity factors) and the hydropower market is highly developed. Investments there are primarily focused on pumped storage projects, as well as refurbishment and modernisation projects to increase the lifespan and efficiency of existing plants and to minimise ecological impacts. Typically, new stations are limited to small, run-of-river facilities (IHA, 2016). In the architecture of the EUCalc, pumped storage capacities are discussed in relation to the Balancing/storage module. In 2015, the EU plus Switzerland had a total 120 GW of hydropower (excluding pumped storage) with 86 GW of that found in only six countries: Austria, France, Italy, Spain, Sweden and Switzerland (Mantzos et al., 2018).

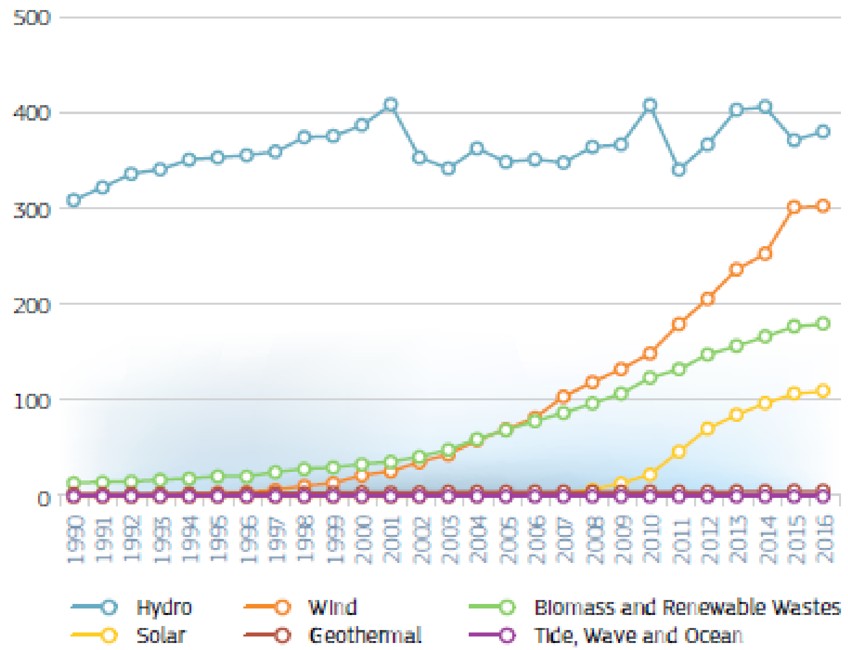


Figure 34 – Gross electricity generation in EU-28 from renewables, 1990-2016 (TWh), source: European Commission, 2018a

Unlike hydropower, penetration of geothermal and marine energy capacities is low, however, like hydropower they are also limited to countries with certain geographical and geological conditions. The term marine energy includes multiple technologies, but the only significant installation of EU is found in France with 240 MW capacity. Apart from that, there are a few small plants of 1-3 MW in the Netherlands, Portugal and UK. Like marine, the bulk of geothermal capacities in EU is also limited to one country: Italy has 879 MW of geothermal electricity production capacity. A few small plants ranging 1-27 MW are in Austria, Cyprus, France, Germany, Greece, Portugal and Romania (Mantzos et al., 2018).

<u>Various scenarios for 2050</u>

The needed geographical and geological conditions to exploit more of these three technologies barely overlap in countries, i.e. there are no countries in the scope of the EUCalc that would have significant further expansion potential for all the three technologies.

For marine energy, according to scenarios from different sources the European total capacity can be in the range of 0-65 GW (Zappa et al., 2019), while the industry association Ocean Energy Europe predicts 100 GW by 2050 (European Commission, 2014b), which is basically the full exploitation of the technical potential. Based on the technical potential future expansion of marine energy is limited to Germany, Denmark, Spain, France, Ireland, the Netherlands, Portugal and UK with France, Ireland and UK responsible for near 90% of the technical potential (for details see below at the description of levels).

For geothermal electricity, according to scenarios from different sources the European total capacity can be in the range of 4-77 GW (Zappa et al., 2019), with a more wide spread application as of today but the bulk of the installations (above 5 GW per country at level 4) projected in France, Germany, Hungary and Spain.

The EU Reference Scenario 2016 predicts 140 GW of hydropower (excluding pumped storage) by 2050, which means 20 GW of growth compared to the current situation (European Commission, 2019). Other sources indicate capacity values around 200 GW; however, it is not clear if pumped storage is included or not (Zappa et al., 2019).

Disaggregation methodology rational

No disaggregation was applied. Trajectories were defined directly on country level.

Feedback from the stakeholder consultations

In general, stakeholders consulted during the co-design workshop agreed with the set of levers proposed. Concrete values, as presented above, were not available at the time of the workshop, thus will be consulted during the call for evidence process.

6.3.6.3 Ambition levels & disaggregation method

The level trajectories were defined using the below sources as starting points; however, they were adjusted by considering the maximal values of electricity demand in 2050 in order to prevent oversupply and stranded assets. The comparison to the maximal electricity demand was carried out on trading zone level[9] in order to account for export-import possibilities in balancing.

For geothermal, the starting data for the most ambitious Level 4 was the potential estimation of Scholz (2012), which is based on detailed assessment of potentials considering geographical constraints and technology development, as detailed in the resource work.

For hydropower, the most ambitious Level 4 is based on the 'ENTSO Scenario 2018 Generation Capacities' Scenario 2040 GCA data[10] and potential estimation by Scholz (2012) (table, Maximum installable capacities in GW, year 2050). The reason for using different sources per country, is the scientific uncertainty in the maximum potential capacity of hydropower technology. Storage capacity for each country was considered based on 'ENTSO Scenario 2018 Generation Capacities' GCA data to determine the maximum hydro (excluding pumped hydro storage) capacity. Datasets per country used:

- The maximum capacity data is derived from 'ENTSO Scenario 2018 Generation Capacities' Scenario 2040 GCA for Belgium, Czech Republic, Germany, Ireland, Lithuania, Luxembourg, Netherlands, Poland, Slovakia, Switzerland and UK. In these cases, this source was the upper limit of maximum capacity (this was the most optimistic projection).
- The maximum capacity data is derived from the work of Scholz for Austria, Bulgaria, Croatia, Cyprus, Denmark, Estonia, Finland, France, Greece, Hungary, Italy, Latvia, Malta, Portugal, Romania, Slovenia, Spain and Sweden. In these cases, this source was the upper limit of maximum capacity (this was the most optimistic projection).

The 2050 value of the Level 1 trajectories of all two technologies are adjusted by the same extent as the potential figures for Level 4.

For geothermal, the less ambitious Level 1 is based on the EU Reference Scenario 2016 (Capros et al., 2016) except for Switzerland. Due to the lack of a reference

[9] for trading zone definition please see deliverable 8.5 "Storage requirements module"

[10] https://www.entsoe.eu/Documents/TYNDP%20documents/TYNDP2018/Scenarios%20Data%20Sets/ENTSO%20Scenario%202018%20Generation%20Capacities.xlsm

scenario for Switzerland and current lack of geothermal capacities, the Level 1 for Switzerland is also set to zero in 2050 (i.e. no geothermal based power generation).

For hydropower (excluding pumped hydro storage), the less ambitious Level 1 is based on the function of the increase between 2020 and 2050 derived from the EU Reference Scenario 2016 (Capros et al., 2016). For the starting data this function is applied on the 2020 data that are the same for each level and reflect a most likely value based on the actual statistical figures. These changes are added to the 2015 data from the JRC IDEES database (Mantzos et al., 2018). The reason for this calculation process is that the reference scenario does not differentiate between primary production hydro capacities and storage hydro capacities. For Switzerland 2015 data was extracted from Hydropower status report 2016 (IHA, 2016).

For geothermal and hydropower technology trajectories, linear interpolation was used for calculating Levels 2 and 3 (i.e. for Level 2, the 2050 value is Level 1 plus one third of the difference between Level 1 and 4, while Level 3 is at two-third of the difference). Values for 2020 are the same for each level and reflect a most likely value based on the actual statistical figures. In some cases, the observed statistical trend between 2015-2017 and 2012-2017 showed already more ambitious target and achievement than reference scenario for 2050, therefore in those cases the 2050 value for the reference scenario was overwritten. From 2020 to 2050, linear interpolation was applied in case of each level trajectories.

The term marine energy includes tidal and wave electricity generation technologies which are relevant in a few European countries. In order to define the countries with relevance and the technical potential, literature assessment was carried out. Table 14 shows the results of the assessment with noting that country level data are scarce in the literature. Potential estimates with larger geographical scopes vary widely, which is due to current high technology costs and uncertainty in future development (European Commission, 2014b).

Table 14 – Marine energy potentials

Country	DE	DK	ES	FR	IE	NL	PT	UK	EU	Source
	Technical potential									
Tidal, GW	0.4	-	0.1	22.8	4.3	1.0		25.2	53.8	Hammons, 2011
Wave, TWh	-	13	50	45	125	-	25	145	403	Schlütter et al., 2015
Wave, GW	-	1.6	5.6	5.1	14.2	-	2.9	16.5	46.0	own calc.*
Total, GW	0.4	1.6	5.7	27.9	18.5	1.0	2.9	41.7	99.8	
Share, %	0.40	1.63	5.74	27.97	18.53	1.00	2.89	41.83	100.00	
	Theoretical potential									
Wave, TWh		32	168	141	467		78	570	1456	Schlütter et al., 2015
Wave, GW		4	19	16	53		9	65	166	Schlütter et al., 2015
Ratio		0.13	0.11	0.11	0.11		0.12	0.11		own calc.

*based on the ratio obtained from the theoretical capacity/production ratio

The sum of the technical potential of 99.8 GW on EU level is identical to industry estimates: the installed capacity could be 100 GW by 2050 (European Commission, 2014b). Therefore, the technical potential figures in Table 14 were considered as basis for Level 4 values in 2050. Basis for the other trajectories is the "The Future of Ocean Energy" leaflet by the European Commission (DG MAF, 2014), as follows:

- basis for Level 1 is the extrapolation of the "option 1: baseline" scenario to 2050 (see Figure 35 as extracted from the leaflet) with breaking down the EU level figure by applying the percentages in Table 14;
- basis for Level 2 is the linear interpolation between level 1 and 3 (i.e. at half of the difference of level 1 and 3 values);
- basis for Level 3 is the extrapolation of the "option 3: targeted structural actions" scenario to 2050 (see Figure 35 as extracted from the leaflet) with breaking down the EU level figure by applying the percentages in Table 14;
- basis for Level 4 are the technical potentials for 2050 as in Table 14, while the trajectory to 2050 is calculated by multiplying the level 3 values by the ratio of 2050 level 4/level 3 ratio (which is 99.8/46.2 = 2.16).

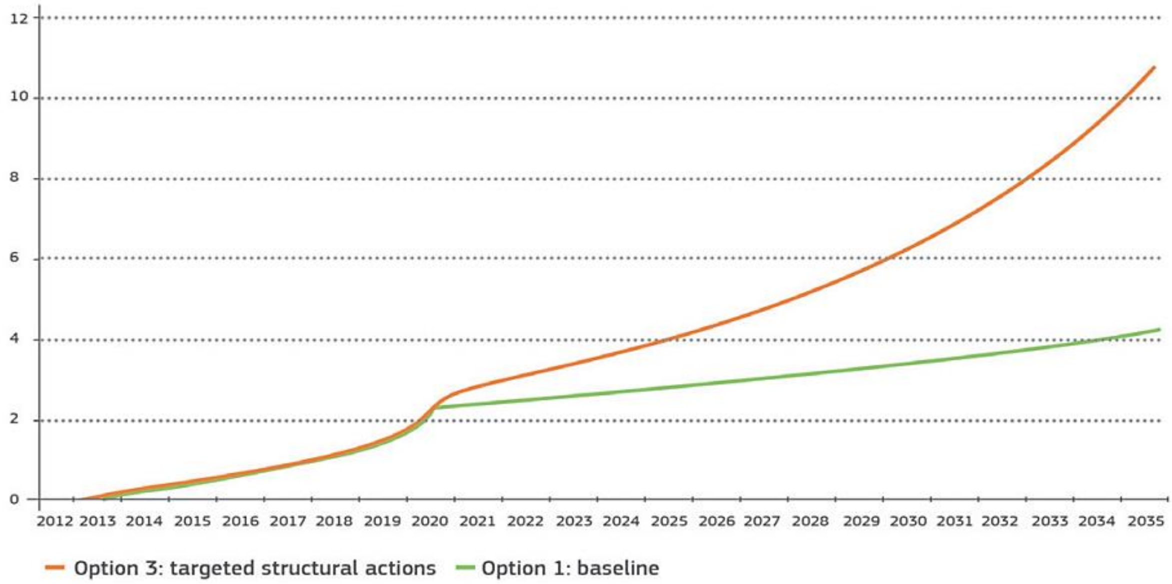


Figure 35 – Expected development of ocean energy installed capacity in the EU until 2035 following targeted structural actions taken by the EU and Member States (option 3) and continuation of the current baseline scenario (option 1 – no actions). Extracted from the "The Future of Ocean Energy" leaflet by DG MAF, 2014

All trajectories have the same value for 2020 and decoupling from there. Table 15 summarizes the figures obtained as described above.

Table 15 – Summary of the other renewables power capacities levels

Country	Geothermal power, GW			Marine power, GW			Hydropower, GW			
	2015/ 2020	2050 L1	2050 L4	2015/ 2020	2050 L1	2050 L4	2015	2020	2050 L1	2050 L4
Austria	0.0	0.0	0.3	0.0	0.0	0.0	8.3	9.0	9.3	15.9
Belgium	0.0	0.0	0.1	0.0	0.0	0.0	0.1	0.1	0.2	2.2
Bulgaria	0.0	0.0	0.9	0.0	0.0	0.0	2.2	2.4	2.5	5.3
Croatia	0.0	0.0	0.5	0.0	0.0	0.0	1.9	1.9	1.9	2.5
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czech Republic	0.0	0.0	0.4	0.0	0.0	0.0	1.1	1.1	1.4	1.6
Denmark	0.0	0.0	0.1	0.0	<0.1	0.2	0.0	0.0	0.0	0.0
Estonia	0.0	0.0	<0.1	0.0	0.0	0.0	0.0	0.0	0.0	<0.1
Finland	0.0	0.0	0.0	0.0	0.0	0.0	3.3	3.4	3.4	3.8
France	0.0	0.0	23.4	0.3	1.5	22.5	18.4	18.7	20.8	29.1
Germany	0.0	0.2	9.4	0.0	0.0	0.4	4.6	4.6	6.0	15.2
Greece	0.0	0.0	1.4	0.0	0.0	0.0	2.7	2.7	2.8	4.0
Hungary	0.0	<0.1	5.4	0.0	0.0	0.0	0.1	0.1	0.2	1.2
Ireland	0.0	0.0	0.0	0.0	0.1	1.3	0.2	0.2	0.2	0.2
Italy	0.9	1.0	4.1	0.0	0.0	0.0	14.5	15.0	15.1	35.0
Latvia	0.0	0.0	<0.1	0.0	0.0	0.0	1.6	1.6	1.6	1.6
Lithuania	0.0	0.0	<0.1	0.0	0.0	0.0	0.1	0.1	0.1	0.3
Luxembourg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	0.0	0.5	0.0	0.1	0.9	0.0	0.0	0.0	2.2
Poland	0.0	0.0	3.0	0.0	0.0	0.0	0.6	0.6	1.0	3.0
Portugal	0.0	0.0	0.0	0.0	<0.1	0.6	4.5	4.5	5.1	7.4
Romania	0.0	0.0	0.6	0.0	0.0	0.0	6.6	6.6	6.6	7.5
Slovakia	0.0	0.0	0.6	0.0	0.0	0.0	1.6	1.6	1.9	3.3
Slovenia	0.0	0.0	0.9	0.0	0.0	0.0	1.1	1.2	1.3	2.4
Spain	0.0	0.0	2.3	0.0	0.1	1.5	14.1	14.1	14.1	21.6
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	16.3	16.3	16.7	17.7
Switzerland	0.0	0.0	0.6	0.0	0.0	0.0	14.7	14.7	17.7	19.8
UK	0.0	0.0	0.3	0.0	0.5	8.0	1.8	2.0	2.1	3.1
EU28+CH Total	1.0	1.3	55.1	0.3	2.5	35.8	120.5	122.8	132.0	207.6

7 Description of constant or static parameters

7.1 Constants list

The following parameters are imported from the technology database:

- lifespan,
- efficiency,
- emission factors,
- self-consumption,
- CAPEX and fixed OPEX as unit costs, as well as their learning rates.

Those parameters are detailed herein first, followed by other constants also used in the module.

7.1.1 Lifespan

Lifespan values are used to calculate the decommission date of new capacities put into operation between 2015 and 2020. The same values, as shown in Table 16, are used for all countries covered. Closure schedules for plants already in operation in 2015 were determined differently, as explained in the calculation logic part.

Table 16 – Lifespan of technologies

Technology	Lifespan, years	Source
Nuclear	60	IEA/NEA OECD, 2015
Coal	40	IEA/NEA OECD, 2015
Natural gas	30	IEA/NEA OECD, 2015
On-shore wind	25	Tsiropoulos et al., 2018
Off-shore wind	30	Tsiropoulos et al., 2018
Solar PV	25	Tsiropoulos et al., 2018
Solar CSP	30	Tsiropoulos et al., 2018
Marine	20	Tsiropoulos et al., 2018
Hydropower	60	Tsiropoulos et al., 2018
Geothermal	30	Tsiropoulos et al., 2018
Biomass	25	Tsiropoulos et al., 2018
Biogas	25	Tsiropoulos et al., 2018

7.1.2 Efficiencies

Electric efficiencies are defined for fossil fuel-based and biomass based power plants in order to calculate the amount of needed input fuel to produce the electricity based on the installed capacities and capacity factors. The values in Table 17 are applied only to the new installations between 2015 and 2050, as for already existing plants in 2015, country specific values are used until their final closure derived from historical data series. The values refer to the starting year of a power plant and are used through its lifespan.

The power plant stock in a country includes solely electricity and combined heat and power (CHP) plants, too which have different efficiency values. The applied mix for new installations is determined based on the base year ratio of CHP plants concerning separately for all types of fossil and biomass plants. The country specific efficiency factors were determined by weighted averages related to CHP and non-CHP power plants.

Table 17 – Efficiency values of thermal power plants,%
For CHP plants the two values denotes the electric/heat production efficiency

Technology	2020	2025	2030	2035	2040	2045	2050	Source
Oil	33	33	33	33	33	33	33	IEA, 2016
Coal	42	43	43	43	43	42	43	IEA, 2016
Coal CHP	32/50	32/50	32/50	32/50	32/50	32/50	32/50	IEA, 2010a
Natural gas	50	50	51	52	52	50	50	IEA, 2016
Natural gas CHP	40/43	40/43	40/43	40/43	40/43	40/43	40/43	IEA, 2010a
Biomass	35	35	39	39	40	40	40	De Vita et al., 2018
Biomass CHP	32/50	32/50	32/50	32/50	32/50	32/50	32/50	IEA, 2010a
Biogas	38	38	38	38	39	39	39	De Vita et al., 2018
Biogas CHP	33/50	33/50	33/50	33/50	33/50	33/50	33/50	IEA, 2010a

7.1.3 Emission factors

Emission factors to calculate CO_2 emissions from the use of coal, natural gas and oil in electricity production are from the IPCC database. The values used in the module, shown in Table 18 are averages of the ones in the database. Like the tier 1 method of the IPCC, those values are used on country level calculations and for all countries.

Table 18 – Emission factors

Fuel	Emission factor, t/GWh input			Source
	CO_2	CH_4	N_2O	
Oil	352.08	-		Gómez et al., 2006
Coal	263.88	-		Gómez et al., 2006
Natural gas	201.96	-		Gómez et al., 2006
Biomass	360.02*	0.0143	0.1092	EPA, 2016
Biogas	177.07*	0.0021	0.0109	EPA, 2016

* in case of biomass based technologies CO2 emission factors is applied only for CCS calculation with negative sign, otherwise CO2 emission is considered as zero

Apart from this, a country specific emission factor (EF) is calculated also for the electricity generation, which is based on the actual composition of the electricity generation mix.

$$spec\ CO2\left(\frac{CO_2 tonne}{TWh\ of\ electricity}\right) = \frac{EF_{coal} \times coal, TWh + EF_{gas} \times gas, TWh + \ EF_{oil} \times oil, TWh}{total\ electricity, TWh}$$

7.1.4 Self-consumption of power plants

Thermal power plants use a ratio of the produced electricity for processes in their own operation. This amount of electricity is expressed as percentage of the produced electricity, thus the electricity available for the grid is reduced by this percentage. Values per technology were collected from the Asset project report (De Vita et al., 2018) and are shown in Table 19. In case of applying carbon capture, the self-consumption is increasing which is also considered in the calculation by using increased self-consumption figures, also from the Asset project report (De Vita et al., 2018).

Table 19 – Self-consumption percentage of power plants

Technology	Self-consumption, %	Self-consumption with carbon capture, %
Nuclear	5	-
Coal	9	30
Natural gas	2	20
Biomass	10	29
Biogas	3	20

7.1.5 Constants for cost calculation

For renewable electricity production technologies a learning rate based method was applied to consider the evolution in costs. For this, base year CAPEX and fixed OPEX values were defined, using a recent JRC study (Tsiropoulos et al., 2018) with calculating the average costs of sub-technologies, shown in Table 20. As no specific learning rate for OPEX could be found, the same learning rates as for CAPEX are describing the OPEX evolution, too.

Table 20 – Basic financial figures of power plants, learning rate approach

Technology	Base year CAPEX, €/kW	Learning rate, %	Base year OPEX, €/kW	Source
On-shore wind	1487	5	45	Tsiropoulos et al., 2018
Off-shore wind	4185	11	84	Tsiropoulos et al., 2018
Solar PV utility	1020	20	17	Tsiropoulos et al., 2018
Solar PV rooftop	1250	20	28	Tsiropoulos et al., 2018
Solar CSP	5470	10	93	Tsiropoulos et al., 2018
Marine	7041	14	390	Tsiropoulos et al., 2018
Hydropower	2848	1	14	Tsiropoulos et al., 2018
Geothermal	7433	5	149	Tsiropoulos et al., 2018
Biomass	3600	5	72	Tsiropoulos et al., 2018
Biogas	3100	5	124	Tsiropoulos et al., 2018

For nuclear and fossil fuel-based technologies the CAPEX and fixed OPEX were defined based on the base year and the 2050 values, as in Table 21, not assuming significant improvements linked to the penetration of technologies. As no new oil-based power plants are foreseen in the model, the costs of that technology are not included.

Table 21 – Basic financial figures of power plants, trajectory approach

Technology	Base year CAPEX, €/kW	Base year OPEX, €/kW	2050 CAPEX, €/kW	2050 OPEX, €/kW	Source
Nuclear	5940	153	4000	149	IEA, 2016
Coal	1890	59	1845	56	IEA, 2016
Natural gas	840	20	840	20	IEA, 2016

7.1.6 Network losses

During the transmission and distribution a certain amount of electricity gets lost. This is considered on EU level by using the value of 6.44% found by World Bank for 2014 (World Bank, 2018). Between 2005 and 2014 (which is the latest data) this value was between 6.2-6.5% in the same source, thus no significant changes in this parameter until 2050 are expected.

7.1.7 Cogenerated heat factor

The annual amount of heat cogenerated in coal, oil, natural gas, as well as biomass and biogas based power plants is calculated by a country specific CHP factor. This expresses the share of electricity (TWh) produced by CHP power plants. The values are derived from historical values in JRC IDEES 2000-2015 and the heat production rate is calibrated to match with the main producer's heat production values reported by Eurostat. The value is different for each country.

For each country the next equations are used:

$$CHP\_elc\_production_X \left(\frac{TWh}{a}\right) = \sum_X factor_{CHP_X} \cdot elc\_production_X$$

$$CHP\_heat\_production_X \left(\frac{TWh}{a}\right) = \sum_X \left(\frac{CHP\_elc\_production_X}{CHP\_elc\_efficiency_X} - CHP\_elc\_production_X\right) \cdot 0.7$$

where x denotes the different fuels used (coal, oil, natural gas, biomass and biogas).

The emission of CHP plants can be divided into two parts, linked to electricity and heat production. The division is based on the efficiency method, published in the WRI/WBSCD GHG protocol (WRI/WBSCD 2006), as shown on the next equation.

$$\begin{aligned} &Emission_{CHP\_heat\_x}\,(Mt) \\ &= \sum_X Emission_{CHP\_x} \frac{\frac{CHP\_heat\_production_X}{CHP\_heat\_efficiency_X}}{\frac{CHP\_heat\_production_X}{CHP\_heat\_efficiency_X} + \frac{CHP\_elc\_production_X}{CHP\_elc\_efficiency_X}} \\ &\cdot elc\_production_X \end{aligned}$$

where *CHP_elc efficiency*$_x$ values were determined by JRC IDEES database for historical data, and literature values for the future (IEA, 2010a), while *CHP_heat_efficiency*$_x$ values were set to 0.7 (based on Eurostat CHP heat values) for historical data, and also for future investments. This above value is solely used to determine the CHP heat specific CO_2 emissions. For real emission of CHP plants the emission factors based on input fuels are used.

$$Emission_{CO2\_CHP\_heat\_specific} \left(\frac{Mt}{TWh}\right) = \frac{\sum_X \cdot Emission_{CHP\_heat\_x}\,(Mt)}{\sum_X CHP\_heat\_production_X (TWh)}$$

7.2 Static parameters

7.2.1 Capacity factors

The capacity factor (CF) expresses the ratio of actual production to a continuous, full capacity production during a period, practically a year, see equation.

$$CF\ (\%) = \frac{actual\ production\ in\ a\ year\ (kWh)}{capacity\ x\ 365{,}25\ x\ 24\ (kWh)}$$

The capacity factor is defined for each technology considered in the electricity generation, however, with different patterns, as shown in Table 22. The capacity factors of PV, wind, hydropower and thermal generation are adjusted by the future impact of climate change based on the input lever choice from the climate module. Tobin et al. assessed the impacts of climate change on wind and solar photovoltaic (among others) power generation in Europe resulting in changes of power generation at different global warming scenarios: +1.5 °C, +2 °C and +3 °C. Based on the climate change scenario selection, i.e. when +1.5 °C and +2 °C are reached globally, the capacity factor is adjusted with the changes (for exact values see next chapter) found by Tobin et al. (2018).

Table 22 – Future patterns of capacity factors per technology

Technology	Definition level	Value	Source
Wind (on and offshore separated)	Country	Trajectories adjusted to climate change scenario	Staffell and Pfenninger, 2016
Solar (PV)	Country	Trajectories adjusted to climate change scenario	Pfenninger and Staffell, 2016
Hydropower	Country	Trajectories adjusted to climate change scenario	Mantzos et al., 2018
Nuclear	Country	Trajectories adjusted to climate change scenario	Mantzos et al., 2018
Coal	Country	Flexible, but only downward regulation for supply-demand gap (implemented in the storage module)	Mantzos et al., 2018
Oil	Country	Trajectories adjusted to climate change scenario	Mantzos et al., 2018
Other RES	Technology	Constant	average of literature sources
Natural gas	Technology	Flexible, up to 85% for supply-demand gap and balancing (implemented in the storage module)	IEA/NEA OECD, 2015

In case of renewable based electricity generation, the capacity factor depends on the climatic conditions (such as solar radiation or wind speed) assuming no curtailment and guaranteed network access. Thus, climate change influences the renewable based electricity production through the changes of the capacity factor. In order to draw the trajectories of capacity factor of renewable based electricity generation technologies, impact of climate change was assessed on the electricity generation by using input from Tobin et al., 2018 as described in the next section.

Base year values for capacity factors per country as extracted from the database of renewables.ninja for wind (Staffell and Pfenninger, 2016) and PV (Pfenninger and Staffell, 2016) are multiplied by a factor accounting for the impact of climate change for every five year to obtain capacity factor trajectories.

Same adjustment is carried out for thermal power plants which are defined on country level (for fossil fuel based and nuclear power generation based on JRC-IDEES dataset) with adjusting the 2015 values. In case of nuclear, it can happen that it is not applied by a country in 2015 but can be present in the future based on lever choice. In this case, a value of 82 % applied based on the average of JRC-IDEES dataset (excluding outliers) for 2015 considering the baseload nature of nuclear limiting the curtailment options. Similarly, for off-shore wind an average of the existing dataset for 2015 by (Staffell and Pfenninger, 2016) was applied for countries expecting new capacities of off-shore wind but base year values were missing.

As of 2015, geothermal and marine power production technologies were operating in industrial scale only in a few countries, thus capacity factors were defined on technology level based on literature sources for all countries expecting new capacities of those technologies in the future:

- for geothermal a value of 75% is set based on IEA report (IEA, 2010b) while values of assessed literature range from 73-80%;
- for marine a value of 35% is set based on the World Energy Council report (WEC, 2016);
- for CSP a value of 28% is set based on the Asset project report (De Vita et al., 2018);
- for biomass and biogas values of 60% and 50%, respectively, based on IEA (IEA, 2016).

Capacity factor of natural gas-based electricity generation largely depends on the operation of the electricity network with quick ramp up time used for balancing. For this reason, the capacity factor for natural gas is linked to its role in balancing of the electricity supply-demand gap as implemented in the storage module. The capacity factor of natural gas can go up to 85% (IEA/NEA OECD, 2015) from the base year country level averages.

7.2.2 Climate change impact on EU power generation

Adopted from the work of Tobin et al. (2018), the following values, as presented in Table 23, are used to adjust capacity factors. The adjustment applies to hydropower, PV, wind (both on- and off-shore) and thermal power generation technologies, each category has its own adjustment value. The climate module provides the year when the temperature change is happening. In between linear interpolation is applied to obtain change values for capacity factors. If the source does not include values for countries, no changes are assumed.

Table 23 – Future changes in national solar PV and wind power productions under +1.5 °C and +2°CC global warming, source: Tobin et al., 2018

Country	Mean change for PV (%) for 1.5°C warming	Mean change for PV (%) for 2°C warming	Mean change for wind (%) for 1.5°C warming	Mean change for wind (%) for 2°C warming
Austria	-1,253	-2,040	-1,369	-0,696
Belgium	-1,708	-2,242	-0,909	-1,836
Bulgaria	-0,226	-0,405	-0,851	-1,436
Croatia	NA	NA	-2,369	-1,429
Cyprus	-0,345	-0,410	-3,974	-4,368
Czech-Rep	-1,568	-2,371	-2,456	-2,015
Denmark	-1,856	-2,500	0,004	-0,848
Estonia	-3,296	-4,620	-0,243	-0,223
Finland	-4,132	-5,875	-1,149	-0,827
France	-1,228	-1,305	-1,864	-3,223
Germany	-1,727	-2,368	-1,368	-2,289
Greece	-0,123	-0,169	1,639	1,947
Hungary	-0,712	-1,237	-2,177	-1,622
Ireland	-1,474	-2,376	-1,168	-2,156
Italy	-0,636	-0,836	-1,210	-2,071
Latvia	-2,645	-4,064	-0,183	0,127
Lithuania	-2,456	-3,839	0,309	0,418
Luxemburg	-1,740	-2,037	-2,759	-3,617
Malta	NA	NA	NA	NA
Netherlands	-1,862	-2,547	-1,216	-2,396
Poland	-1,775	-2,955	-1,419	-1,770
Portugal	0,213	0,444	-0,914	-2,831
Romania	-0,494	-0,953	-0,888	-0,589
Slovakia	-1,110	-1,903	NA	NA
Slovenia	NA	NA	-1,214	0,038
Spain	-0,067	-0,072	-0,038	-1,691
Sweden	-3,498	-5,038	-0,732	-1,205
Switzerland	-1,566	-2,239	-1,962	-2,177
UK	-1,345	-2,033	-0,670	-1,569

8 Historical database

8.1 Database for electricity production

Table 24 – Database for electricity production

Dataset	Description	Main sources	Data quality check	Hypotheses
Wind power generation capacities [GW]	Historical capacities (on- and off-shore) by country	• Total wind power generation capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • Total wind power generation capacities 2005 to 2014, for Switzerland: TSP Data Portal (TSP, 2018) • Total wind power generation capacities 2015, for Switzerland: Swiss Federal Office of Energy (Kaufmann, 2016) • Off-shore wind power generation capacities 2015 by country: EWEA, 2016b • Off-shore wind power generation capacities 2014 by country: EWEA, 2015 • Off-shore wind power generation capacities	• No data available before 2000 (for Switzerland prior to 2005) • No data available separately for off-shore wind prior 2009 • Good quality data from reliable, coherent and credible sources • Coherence between TSP and Swiss data for 2015?	• On-shore wind power generation capacities equal to total wind power generation capacities by JRC-IDEES minus off-shore wind power generation capacities by EWEA • All wind power generation capacities were installed after 1999 (after 2004 for Switzerland) • All off-shore wind power generation capacities were installed after 2008

		2013 by country: EWEA, 2014 • Off-shore wind power generation capacities 2012 by country: EWEA, 2013 • Off-shore wind power generation capacities 2011 by country: EWEA, 2012 • Off-shore wind power generation capacities 2010 by country: EWEA, 2011 • Off-shore wind power generation capacities 2009 by country: EWEA, 2010		
Solar power generation capacities [GW]	Historical capacities (PV and CSP) by country	• PV generation capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • PV generation capacities 2005 to 2014, for Switzerland: TSP Data Portal (TSP, 2018) • PV generation capacities 2015, for Switzerland: Swiss Federal Office of Energy (Kaufmann, 2016) • Solar thermal (CSP) generation capacities 2000 to 2015, by country (expect Switzerland): JRC-	• No data available before 2000 (for Switzerland prior to 2005) • Good quality data from reliable, coherent and credible sources • Coherence between TSP and Swiss data for 2015?	• All PV and CSP capacities were installed after 1999 (after 2004 in Switzerland) • No CSP in Switzerland

		IDEES (Mantzos et al., 2018)		
Other renewables based generation capacities [GW]	Historical capacities (hydropower excluding storage, marine and geothermal) by country	• Hydropower capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • Marine power capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • Geothermal power capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • Hydropower capacities 1990 to 1999, by country: TSP Data Portal (TSP, 2018) • Hydropower capacities 1990 to 2014, for Switzerland: TSP Data Portal (TSP, 2018) • Geothermal power capacities 2005 to 2014, for Switzerland: TSP Data Portal (TSP, 2018) • Hydropower capacities 2015, for Switzerland: Swiss Federal Office of Energy (Kaufmann, 2016)	• No data for geothermal and marine available before 2000 (for Switzerland prior to 2005) • Good quality data from reliable, coherent and credible sources	• All geothermal and marine power capacities were installed after 1999 • No geothermal power in Switzerland

Nuclear generation capacities [GW]	Historical gross capacities of nuclear power by country	• Nuclear power capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • Nuclear power capacities 1990 to 1999, by country: TSP Data Portal (TSP, 2018) • Nuclear power capacities 1990 to 2014, for Switzerland: TSP Data Portal (TSP, 2018)	• No data for Switzerland for the base year (2015) • Good quality data from reliable, coherent and credible sources	• While JRC IDEES data are gross capacity values, TSP data are assumed (though not consistent) to be net values. Thus, the ratio of TSP/JRC IDEES values were calculated for data between 2000-2014 where both datasets are available. This ratio is then applied to TSP data between 1990-1999.
Fossil fuel based generation capacities [GW]	Historical gross capacities of coal, oil and natural gas based power plants by country	• Coal power plant capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • Oil power plant capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • Natural gas power plant capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • Values prior 2000 are calculated from data of the TSP Data Portal.	• No separate data are available prior 2000, TPS Data Portal includes only Fossil fuels not broken down further • No data for Switzerland	• Coal based capacity is the sum of coal fired and lignite fired categories within JRC IDEES. • Natural gas based capacity is the sum of gas fired, derived gas fired and refinery gas fired categories within JRC IDEES. • Oil based capacity is the sum of diesel oil fired and fuel Oil fired categories within JRC IDEES. • No separate data are available prior 2000, just aggregated fossil fuel capacity values in the TSP Data Portal. As electricity production, however, is available per energy carrier from the TSP Data Portal, the separate coal, oil and natural gas capacities were estimated as described here for the period 1990-1999. An annual average fossil fuel capacity factor was calculated by using the total fossil capacities and the sum of the electricity produced from sources coal, oil and gas. The equation is: (actual production from coal, xWh + actual

				production from oil, xWh + actual production from gas, xWh)/(total fossil fuel capacities x 365,25 x 24). This country specific average capacity factor was used to calculate capacities per energy carriers by using the next equations: coal based capacities, xW = actual production from coal, xWh/(avarage fossil capacity factor x 365,25 x 24); oil based capacities, xW = actual production from oil, xWh/(avarage fossil capacity factor x 365,25 x 24); gas based capacities, xW = actual production from gas, xWh/(avarage fossil capacity factor x 365,25 x 24).
Biomass based electricity generation [GW]	Historical gross capacities for biomass based electricity generation	• Biomass based plant capacities 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018)	• No data for Switzerland	
Capacity factor [%]	Historical capacity factors for all technologies by country	• For all technologies (except PV and wind) 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) • For on- and off-shore wind separately 1990 to 2015, by country: renewables.ninja (Staffell and Pfenninger, 2016) • For PV 1990 to 2015, by country: renewables.ninja	• No separate data are available prior 2000, TPS Data Portal includes only Fossil fuels not broken down further • Limited data for Switzerland	• Assumption for Swiss values? • As no separate data by energy carrier are available prior 2000, just aggregated fossil fuel capacity values and production in the TSP Data Portal, an annual average fossil fuel capacity factor was calculated by using the total fossil capacities and the sum of the electricity produced from sources coal, oil and gas, and this value is used in this period for all fossil energy carriers The equation is: (actual production from coal, xWh + actual production from oil, xWh + actual production from gas, xWh)/(total fossil fuel capacities x 365,25 x 24).

		(Pfenninger and Staffell, 2016) • For nuclear, fossil fuel and hydroelectricity prior to 2000 and for Switzerland data from TSP Data Portal were used.		• For nuclear and hydroelectricity, prior 2000 and for Switzerland the annual actual electricity production was divided by the maximal theoretical production: capacity value x 365,25 x 24, both data gathered from the TSP Data Portal. • For the other renewables based production no significant capacities are assumed prior 2000.
Efficiencies [%]	Historical capacity factors for fossil fuel based technologies by country	• For all technologies 2000 to 2015, by country (expect Switzerland): JRC-IDEES (Mantzos et al., 2018) (gross electric efficiencies)	• No data for Switzerland	• Coal power plant efficiency is the weighted average of coal fired and lignite fired categories within JRC IDEES. • Natural gas power plant efficiency is the weighted average of gas fired, derived gas fired and refinery gas fired categories within JRC IDEES. • Oil power plant efficiency is the weighted average of diesel oil fired and fuel Oil fired categories within JRC IDEES. • As no separate data per energy carrier are available prior 2000, the trends of 2000-2015 were used to estimate the values between 1990-1999. Observing the linearity of the trends between 2000-2015, the TREND function of Microsoft Excel was applied to estimate values of 1990-1999. This finds the linear trend by using the least squares method to calculate the line of best fit for a supplied set of y- and x-values (in this case y values are the efficiencies, x values the years of 2000-2015). For a given year between 1990-1999 the value provided this by method was used unless it was larger than the country averages (excluding

				outliers) of the 2000-2015 values. In this latter case, the average value (without outliers) was used.
Produced amount of biogas [TWh]	Historical production of biogas from different sources per country.	• Eurostat Primary production annual data [nrg_109a]: Biogas, Landfill gas, Sewage Sludge Gas	• No data for Switzerland	•
Combined Heat and Power data	Historical database about EU-28 CHP production	• Eurostat Combined Heat and Power (CHP) data	• No data for Switzerland • No data prior 2005	

9 References

Aitani, AM (2004) Oil Refining and Products. Encyclopedia of Energy 4:715-729

BNEF, BloombergNEF (2018a) EU Nations' Coal-Exit Plans in 2018 to Benefit Renewables, 22 Jan 2018. [Online]. Available: https://about.bnef.com/blog/eu-nations-coal-exit-plants-in-2018-to-benefit-renewables/ [Accessed 28 May 2019]

BNEF, Bloomberg NEF (2018b) Bloomberg Expects 1,400 GW PV For Europe By 2050, Taiyang News, 7 Nov 2018 [Online] Available: http://taiyangnews.info/markets/bloomberg-expects-1400-gw-pv-for-europe-by-2050/ [Accessed 28 May 2019]

C3E (2019) Status Report on Gender Equality in the Energy Sector, brochure

CAN Europe (2015) Coal map of Europe, http://coalmap.eu/#/downloads

Capros, P, Höglund-Isaksson, L, Winiwarter, W, Purohit, P, Gomez-Sanabria, A, Frank, S, Forsell, N, Gusti, M, Havlík, P, Obersteiner, M, Witzke H, Kesting, M (2016) EU Reference Scenario 2016: Energy, transport and GHG emissions trends to 2050, European Commission

Carbon Tracker (2017) Lignite of the Living Dead

Climate Analytics (2017) A stress test for coal in Europe under the Paris Agreement

Climate Analytics (2019) Coal Phase Out in the EU - Detailed Information [Online] Available: https://climateanalytics.org/briefings/eu-coal-phase-out/eu-coal-phase-out-detailed-information/ [Accessed 28 May 2019]

CONCAWE (2019) Refinery Sites in Europe [Online] Available: https://www.concawe.eu/refineries-map/ [Accessed 28 May 2019]

De Vita, A, Kielichowska, I, Mandatowa, P (2018) Technology pathways in decarbonisation scenarios. ASSET project

DG MAF, Directorate-General for Maritime Affairs and Fisheries (2014) The future of ocean energy

E3MLab & IIASA (2016) Technical report on Member State results of the EUCO policy scenarios

EEA, European Environment Agency (2018) Annual European Union greenhouse gas inventory 1990–2016 and inventory report 2018. European Environment Agency, Brussels, Belgium

EPA, United States Environmental Protection Agency (2016) Greenhouse Gas Inventory Guidance Direct Emissions from Stationary Combustion Sources

EUobserver (2018) CO2 storage still needed for carbon-neutral EU in 2050, 28 Nov 2018 [Online] Available: https://euobserver.com/environment/143512 [Accessed 28 May 2019]

EurObserv'ER (2017) Solar thermal and concentrated solar power barometer 2017

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730459.

European Commission (2009) Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC

European Commission (2013) Summary report on the analysis of the responses received to the Consultative Communication on the future of Carbon Capture and Storage in Europe [COM(2013)180]

European Commission (2014a) A policy framework for climate and energy in the period from 2020 to 2030 (COM/2014/015 final)

European Commission (2014b) Impact Assessment - Ocean Energy: Action needed to deliver on the potential of ocean energy by 2020 and beyond

European Commission (2018a) EU energy in figures - Statistical Pocketbook 2018. Publications Office of the European Union

European Commission (2018b) A Clean Planet for all - A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. COM(2018)773

European Commission (2019) Energy Modelling [Online] Available: https://ec.europa.eu/energy/en/data-analysis/energy-modelling [Accessed 28 May 2019]

European Parliament (2019) Women, Gender Equality and the Energy Transition in the EU. [Online] Available: http://www.europarl.europa.eu/supporting-analyses [Accessed 15 October 2019]

European Union (2008) Consolidated version of the Treaty on the Functioning of the European Union

EuroStat (2017) Energy balance sheets 2015 (2017 edition)

EuroStat (2018) Energy production and imports [Online] Available: https://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_production_and_imports [Accessed 28 May 2019]

EWEA, European Wind Energy Association (2010) The European offshore wind industry - key trends and statistics 2009

EWEA, European Wind Energy Association (2011) The European offshore wind industry key trends and statistics 2010

EWEA, European Wind Energy Association (2012) The European offshore wind industry key 2011 trends and statistics

EWEA, European Wind Energy Association (2013) The European offshore wind industry - key trends and statistics 2012

EWEA, European Wind Energy Association (2014) The European offshore wind industry - key trends and statistics 2013

EWEA, European Wind Energy Association (2015) The European offshore wind industry - key trends and statistics 2014

EWEA, European Wind Energy Association (2016a) Wind in power - 2015 European statistics

EWEA, European Wind Energy Association (2016b) The European offshore wind industry - key trends and statistics 2015

Farfan, J and Breyer, C (2017) Aging of European power plant infrastructure as an opportunity to evolve towards sustainability. International Journal of Hydrogen Energy 42(28):18081-18091

Fraune, C (2015) Gender matters: Women, renewable energy, and citizen participation in Germany. Energy Research & Social Science 7:55-65

FuelsEurope (2017) Statistical report 2017

FuelsEurope (2019) Diesel/gasoline imbalance [Online]. Available: https://www.fuelseurope.eu/knowledge/how-refining-works/dieselgasoline-imbalance/ [Accessed 28 May 2019]

Glass, C, Cook, A, Ingersoll, AR (2016) Do Women Leaders Promote Sustainability? Analyzing the Effect of Corporate Governance Composition on Environmental Performance. Business Strategy & the Environment 25(7):495–511

Global CCS Institute (2019) Facilities Database [Online] Available: https://co2re.co/StorageData [Accessed 28 May 2019]

Global Energy Monitor (2019) Global Coal Plant Tracker [Online] Available: https://endcoal.org/tracker/ [Accessed 28 May 2019]

Greenpeace and CAN, Climate Action Network Europe (2015) End of an Era: Why every European country needs a coal phase-out plan, London, UK/Brussels, Belgium

Gómez, DR, Watterson, JD, Americano, BB, Ha, C, Marland, G, Matsika, E, Namayanga, LN, Osman-Elasha, B, Saka, JDK, Treanton, K (2006) 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Chapter 2: Stationary Combustion. IPCC

Hammons, T (2011) Energy Potential of the Oceans in Europe and North America: Tidal, Wave, Currents, OTEC and Offshore Wind. in Electricity Infrastructures in the Global Marketplace, IntechOpen, 153-194

Hübler, M and Löschel, A (2013) The EU Decarbonisation Roadmap 2050 - What way to walk? Energy Policy 55:190-207

IAEA, International Atomic Energy Agency (2018) Energy, Electricity and Nuclear Power Estimates for the Period up to 2050

IEA, International Energy Agency (2010a) Energy Systems Technology Analysis Program Technology Brief E04. Available: https://iea-etsap.org/index.php/energy-technology-data/energy-supply-technologies-data

IEA, International Energy Agency (2010b) Renewable Energy Essentials: Geothermal

IEA, International Energy Agency (2018) Coal 2018 Analysis and forecasts to 2023 [Online] Available: https://www.iea.org/coal2018/ [Accessed 28 May 2019]

IEA, International Energy Agency (2019) World Energy Investment 2019

IEA/NEA OECD (2015) Projected Costs of Generating Electricity 2015 Edition

IEA, International Energy Agency (2016) Power generation assumptions in the New Policies and 450 Scenarios in the World Energy Outlook 2016 [Online] Available: http://www.iea.org/media/weowebsite/energymodel/WEO_2016_PG_Assumptions_NPSand450_Scenario.xlsb

IHA, International Hydropower Association (2016) Hydropower status report 2016

IRENA, International Renewable Energy Agency (2018) Renewable Energy Prospects for the European Union

IRENA, International Renewable Energy Agency (2019) Renewable Energy: A Gender Perspective

Jager-Waldau, A (2017) PV Status Report 2017, Publications Office of the European Union, Luxembourg

JODI-Oil, Joint Organisations Data Initiative Oil (2019) JODI Oil World Database, Joint Organisations Data Initiative Oil (JODI-Oil), [Online]. Available: https://www.jodidata.org/oil/ [Accessed 28 May 2019]

Kaufmann, U (2016) Schweizerische Statistik der erneuerbaren Energien Ausgabe 2015, Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation UVEK

Kinnon, MAM, Brouwer J, Samuelsen, S (2018) The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration. Progress in Energy and Combustion Science 64:62-92

Mantzos, L, Matei, N, Mulholland, E, Rózsai, M, Tamba, M, Wiesenthal, T (2018) JRC-IDEES 2015 (Dataset) PID: http://data.europa.eu/89h/jrc-10110-10001 European Commission, Joint Research Centre (JRC)

Nighiem, A, Pineda I, Tardieu, P (2017) Wind energy in Europe: Scenarios for 2030, Wind Europe

Odenberger, M, Kjarstad, J, Johnsson, F (2013) Prospects for CCS in the EU Energy Roadmap to 2050. Energy Procedia 37:7573-7581

OPEC, Organization of the Petroleum Exporting Countries (2017) 2017 OPEC World Oil Outlook

Pfenninger, S and Staffell, I (2016) Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. Energy 114:1251-1265

Schlütter, F, Petersen, OS, Nyborg, L (2015) Resource Mapping of Wave Energy Production in Europe. in Proceedings of the 11th European Wave and Tidal Energy Conference 6-11th Sept 2015, Nantes, France

Schneider, M, Froggatt, A, Hazemann, J, Katsuta, T, Ramana, M, Thomas, S (2015) The World Nuclear Industry Status Report 2015

Scholz, Y (2012) Renewable energy based electricity supply at low costs: development of the REMix model and application for Europe. PhD Thesis, University of Stuttgart, 2012

SolarPowerEurope (2018) Global Market Outlook for Solar Power 2018-2022

Staffell, I and Pfenninger, S (2016) Using Bias-Corrected Reanalysis to Simulate Current and Future Wind Power Output. Energy 114:1224–1239

Tobin, I, Greuell, W, Jerez, S, Ludwig, F, Vautard, R, van Vliet, MTH, Bréon, FM (2018) Vulnerabilities and resilience of European power generation to 1.5 °C, 2 °C and 3 °C warming. Environmental Research Letters 13(4)

Tsiropoulos, I, Tarvydas, D, Zucker, A (2018) Cost development of low carbon energy technologies - Scenario-based cost trajectories to 2050, 2017 Edition

TSP, The Shift Project (2018) The Shift Project Data Portal, TSP Data [Online] Available: http://www.tsp-data-portal.org

Wildenborg, T, Coussy, P, Doukelis, A, Ekstrom, C, Georgiou, G, Gkountanis, S, Kramers, L, van der Kuip, M, Lindeberg, E, Nordbo, O, Serbutoviez S, Simonsson, D (2009) Scenario for large-scale implementation of CCS in Europe. Energy Procedia 1(1):4265-4272

WEC, World Energy Council (2016) World Energy Resources: Marine Energy 2016

Wind Europe (2018) Wind in power 2017 - Annual combined onshore and offshore wind energy statistics

WNA, World Nuclear Association (2018) Nuclear Power in the European Union, July 2018 [Online] Available: http://www.world-nuclear.org/information-library/country-profiles/others/european-union.aspx [Accessed 28 May 2019]

WNA, World Nuclear Association (2019) Information Library [Online] Available: http://www.world-nuclear.org/information-library.aspx [Accessed 28 May 2019]

World Bank (2018) Electric power transmission and distribution losses (% of output), IEA, 2018 [Online] Available: https://data.worldbank.org/indicator/EG.ELC.LOSS.ZS?locations=EU [Accessed 28 May 2019]

WRI/WBSCD (2006) Allocation of GHG Emissions from a Combined Heat and Power (CHP) Plant, Guide to calculation worksheets, A WRI/WBSCD GHG Protocol Initiative calculation tool. Available: https://ghgprotocol.org/sites/default/files/CHP_guidance_v1.0.pdf

Zappa, W, Junginger, M, van den Broek, M (2019) Is a 100% renewable European power system feasible by 2050? Applied Energy 233-234:1027-1050

10 Annexes

10.1 Nuclear policies of countries

The table shows the nuclear policies per countries as of 2018. These policies had been considered when defining the ambition levels per countries.

	Nuclear policy	Capacities in 2015?	New capacities?	Levels defined?	Source
AT	anti-nuclear policy	NO	NO	NO	link
BE	phase-out by 2025	YES	NO	YES	link
BG	new plants planned	YES	YES	YES	link
HR	neutral?	NO	NO	NO	no sources found
CY	neutral?	NO	NO	NO	no sources found
CZ	new plants planned	YES	YES	YES	link
DK	anti-nuclear policy	NO	NO	NO	link
EE	new plants planned but source date only to 2009	NO	YES	YES	link
FI	new plants planned	YES	YES	YES	link
FR	decrease ratio?	YES	NO	YES	link
DE	phase-out	YES	NO	YES	link
GR	anti-nuclear policy	NO	NO	NO	link
HU	new plants planned	YES	YES	YES	link
IE	anti-nuclear policy	NO	NO	NO	link
IT	anti-nuclear policy	NO	NO	NO	link
LV	neutral?	NO	NO	NO	no sources found
LT	new plants planned	NO	YES	YES	link
LU	anti-nuclear policy	NO	NO	NO	link
MT	neutral?				no sources found
NL	no new planned	YES	NO	YES	link
PL	new plants planned	NO	YES	NO	link
PT	no nuclear	NO	NO	NO	
RO	new plants planned	YES	YES	YES	link
SK	new plants only for substitution	YES	YES	YES	link
SI	new plants planned	YES	YES	YES	link
SP	phase out?	YES	NO	YES	link
SE	new plants planned	YES	YES	YES	link
CH	phase-out	YES	NO	YES	link
UK	new plants planned	YES	YES	YES	link

10.2 Details of bottom-up, power plant based nuclear power ambition levels

Based on the above policies and the country profiles of World Nuclear Association the levels were defined for indicated countries in the above table.

The below tables list all the operational nuclear power plants in 2015, as well as announced new plants in yellow fields. For plants the actual or proposed capacity values are listed and for operating plants in 2015 the commission date. For each power plant, four possible dates are indicated as closing year or for new plants as star dates. Per power plant the dates can be the same, however, if aggregating the dates to get the levels, those differ aligned to the general level definitions.

Bottom of the table, sparklines show trends of capacity changes by level with red dot for the 2015 value and zero as minimal value. The maximum value depends on country, and chosen as the highest potential capacity level across ambitions, thus for a country each sparkline has the same maximum value set.

There is a difference observed between the 2015 value from the historical database of JRC-IDEES and the sum of bottom-up method with data from World Nuclear Association, as presented in the below table. The reason for this is that historical series are gross capacities, while future timeseries, as defined this way by the World Nuclear Association, are either net or gross capacities. In order to make data series coherent, values in future time series were corrected by the ratio of 2015 historical gross values (JRC-IDEES) and 2015 value by the World Nuclear Association.

General sources for the capacity values, licences, start date and future life of power plants are the country profiles of the World Nuclear Association available from the main site of World Nuclear Power Reactors & Uranium Requirements [11] complemented with country level specific sources on nuclear policies.

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Belgium	Doel 1	433	1974	2020	2020	2020	2025
Belgium	Doel 2	433	1975	2020	2020	2020	2025
Belgium	Doel 3	1,006	1982	2020	2025	2025	2030
Belgium	Doel 4	1,047	1985	2020	2025	2025	2030
Belgium	Tihange 1	962	1975	2020	2025	2025	2025
Belgium	Tihange 2	1,008	1982	2020	2025	2025	2030
Belgium	Tihange 3	1,054	1985	2020	2025	2025	2030
BE TOTAL 2015		5,943					
	Belgium Nucler Power Lever Sparklines, 2015-2050						

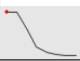
Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Bulgaria	Kozloduy 5	963	1987	2045	2045	2045	2045
Bulgaria	Kozloduy 6	963	1991	2050	2050	2050	2050
Bulgaria	Kozloduy 7	1,200		cancelled	2035	2030	2025
Bulgaria	Belene	2,000		cancelled	cancelled	2040	2030
BG TOTAL 2015		1,926					
	Bulgaria Nucler Power Lever Sparklines, 2015-2050						

[11] http://www.world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme.aspx

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Czech Republic	Dukovany 1	468	1985	2030	2030	2030	2040
Czech Republic	Dukovany 2	471	1986	2035	2035	2035	2045
Czech Republic	Dukovany 3	468	1986	2035	2035	2035	2045
Czech Republic	Dukovany 4	471	1987	2035	2035	2035	2045
Czech Republic	Temelin 1	1,023	2000	2040	2040	2040	2050
Czech Republic	Temelin 2	1,003	2003	2040	2040	2040	2050
Czech Republic	Dukovany 5	1,200		cancelled	2040	2030	2030
Czech Republic	Temelin 3	1,200		cancelled	2040	2030	2030
Czech Republic	Temelin 4	1,200		cancelled	cancelled	2035	2035
CZ TOTAL 2015		3,904					
Czech Republic Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Estonia		1,000		cancelled	2040	2035	2030
EE TOTAL 2015							
Estonia Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Finland	Loviisa 1	502	1977	2025	2025	2025	2025
Finland	Loviisa 2	502	1980	2025	2025	2025	2025
Finland	Olkiluoto 1	880	1978	2035	2035	2035	2035
Finland	Olkiluoto 2	880	1980	2035	2035	2035	2035
Finland	Olkiluoto 3	1,600		2020	2020	2020	2020
Finland	Hanhikivi 1	1,200		cancelled	2035	2030	2025
FI TOTAL 2015		2,764					
Finland Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
France	Blayais 1	910	1981	2020	2020	2040	2040
France	Blayais 2	910	1983	2020	2020	2040	2040
France	Blayais 3	910	1983	2020	2020	2040	2040
France	Blayais 4	910	1983	2020	2020	2040	2040
France	Bugey 2	910	1979	2020	2020	2035	2035
France	Bugey 3	910	1979	2020	2020	2035	2035
France	Bugey 4	880	1979	2020	2020	2035	2035
France	Bugey 5	880	1980	2020	2020	2040	2040
France	Chinon B 1	905	1984	2020	2020	2040	2040
France	Chinon B 2	905	1984	2020	2020	2040	2040
France	Chinon B 3	905	1987	2025	2025	2045	2050
France	Chinon B 4	905	1988	2025	2025	2045	2050
France	Cruas 1	915	1984	2020	2020	2040	2040
France	Cruas 2	915	1985	2025	2025	2045	2050
France	Cruas 3	915	1984	2020	2020	2040	2040
France	Cruas 4	915	1985	2025	2025	2045	2050
France	Dampierre 1	890	1980	2020	2020	2040	2040
France	Dampierre 2	890	1981	2020	2020	2040	2040
France	Dampierre 3	890	1981	2020	2020	2040	2040
France	Dampierre 4	890	1981	2020	2020	2040	2040
France	Fessenheim 1	880	1977	2015	2015	2015	2015
France	Fessenheim 2	880	1978	2015	2015	2015	2015
France	Gravelines B 1	910	1980	2020	2020	2040	2040
France	Gravelines B 2	910	1980	2020	2020	2040	2040
France	Gravelines B 3	910	1981	2020	2020	2040	2040
France	Gravelines B 4	910	1981	2020	2020	2040	2040
France	Gravelines C 5	910	1985	2025	2025	2045	2050
France	Gravelines C 6	910	1985	2025	2025	2045	2050
France	Saint-Laurent B 1	915	1983	2020	2020	2040	2040
France	Saint-Laurent B 2	915	1983	2020	2020	2040	2040
France	Tricastin 1	915	1980	2020	2020	2040	2040
France	Tricastin 2	915	1980	2020	2020	2040	2040
France	Tricastin 3	915	1981	2020	2020	2040	2040
France	Tricastin 4	915	1981	2020	2020	2040	2040
France	Belleville 1	1,310	1988	2025	2025	2045	2050
France	Belleville 2	1,310	1989	2025	2025	2045	2050
France	Cattenom 1	1,300	1987	2025	2025	2045	2050
France	Cattenom 2	1,300	1988	2025	2025	2045	2050
France	Cattenom 3	1,300	1991	2025	2030	2050	2050
France	Cattenom 4	1,300	1992	2025	2030	2050	2050
France	Flamanville 1	1,330	1986	2025	2025	2045	2050
France	Flamanville 2	1,330	1987	2025	2025	2045	2050
France	Flamanville 3	1,750	2020	2025	2050	2050	2050
France	Golfech 1	1,310	1991	2025	2030	2050	2050
France	Golfech 2	1,310	1994	2025	2030	2050	2050
France	Nogent s Seine 1	1,310	1988	2025	2025	2045	2050
France	Nogent s Seine 2	1,310	1989	2025	2025	2045	2050
France	Paluel 1	1,985	1985	2025	2025	2045	2050
France	Paluel 2	1,985	1985	2025	2025	2045	2050
France	Paluel 3	1,986	1986	2025	2025	2045	2050
France	Paluel 4	1,986	1986	2025	2025	2045	2050
France	Penly 1	1,330	1990	2025	2030	2050	2050
France	Penly 2	1,330	1992	2025	2030	2050	2050
France	Saint-Alban 1	1,335	1986	2025	2025	2045	2050
France	Saint-Alban 2	1,335	1987	2025	2025	2045	2050
France	Chooz B 1	1,500	1996	2025	2035	2050	2050
France	Chooz B 2	1,500	1999	2025	2035	2050	2050
France	Civaux 1	1,495	1999	2025	2035	2050	2050
France	Civaux 2	1,495	2000	2025	2040	2050	2050
FR TOTAL 2015		65,752					
France Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Germany	Gundremmingen B	1,284	1984	2020	2020	2020	2030
Germany	Gundremmingen C	1,288	1985	2020	2020	2025	2035
Germany	Grohnde	1,360	1985	2020	2020	2025	2035
Germany	Philipsburg 2	1,392	1986	2015	2015	2015	2015
Germany	Brokdorf	1,370	1988	2020	2020	2025	2035
Germany	Isar 2	1,400	1988	2020	2020	2025	2035
Germany	Emsland	1,329	1988	2020	2020	2025	2035
Germany	Neckarwestheim 2	1,305	1989	2020	2020	2025	2035
DE TOTAL 2015		10,728					
Germany Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Hungary	Paks 1	470	1982	2030	2030	2030	2030
Hungary	Paks 2	473	1984	2030	2030	2030	2030
Hungary	Paks 3	473	1986	2035	2035	2035	2035
Hungary	Paks 4	473	1987	2035	2035	2035	2035
Hungary	Paks 5	1,200		cancelled	2030	2025	2025
Hungary	Paks 6	1,200		cancelled	2030	2030	2025
HU TOTAL 2015		1,889					
Hungary Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Lithuania	Visagina 1	1,200		cancelled	2045	2040	2030
LT TOTAL 2015							
Lithuania Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Netherlands	Brosselle	485	1973	2020	2025	2030	2035
NL TOTAL 2015		485					
Netherlands Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Poland	site 1	3,000		cancelled	2035	2030	2025
Poland	site 2	3,000		cancelled	2040	2035	2030
PL TOTAL 2015							
Poland Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Romania	Cernavoda 1	650	1996	2045	2045	2045	2050
Romania	Cernavoda 2	650	2007	2050	2050	2050	2050
Romania	Cernavoda 3	720		cancelled	2035	2030	2025
Romania	Cernavoda 4	720		cancelled	2035	2030	2025
RO TOTAL 2015		1,300					
Romania Nucler Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Slovakia	Bohunice V2 1	472	1984	2020	2020	2020	2050
Slovakia	Bohunice V2 2	472	1985	2025	2025	2025	2050
Slovakia	Mochovce 1	436	1998	2045	2045	2045	2050
Slovakia	Mochovce 2	436	1999	2045	2045	2045	2050
Slovakia	Mochovce 3	440	2019	2050	2050	2050	2050
Slovakia	Mochovce 4	440	2019	2050	2050	2050	2050
Slovakia	Bohunice new	1,200		cancelled	2035	2025	2025
Slovakia	Kecerovce	1,200		cancelled	cancelled	2030	2030
SK TOTAL 2015		1,816					
	Slovakia Nucler Power Lever Sparklines, 2015-2050						

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Slovenia	Krsko 1	696	1981	2045	2045	2045	2045
Slovenia	Krsko new	1,100		cancelled	2045	2040	2035
SI TOTAL 2015		696					
	Slovenia Nucler Power Lever Sparklines, 2015-2050						

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Spain	Almaraz 1	1,011	1981	2020	2030	2030	2030
Spain	Almaraz 2	1,006	1983	2020	2020	2025	2030
Spain	Asco 1	995	1983	2020	2020	2025	2030
Spain	Asco 2	997	1985	2020	2025	2030	2035
Spain	Cofrentes	1,064	1984	2020	2020	2025	2030
Spain	Trillo 1	1,003	1988	2020	2025	2030	2035
Spain	Vandellos 2	1,045	1987	2020	2025	2030	2035
SP TOTAL 2015		7,121					
	Spain Nucler Power Lever Sparklines, 2015-2050						

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Sweden	Oskarshamn 3	1,400	1985	2045	2045	2045	2045
Sweden	Ringhals 1	878	1976	2020	2020	2020	2020
Sweden	Ringhals 2	807	1975	2015	2015	2015	2015
Sweden	Ringhals 3	1,062	1981	2040	2040	2040	2040
Sweden	Ringhals 4	938	1983	2040	2040	2040	2040
Sweden	Forsmark 1	984	1980	2040	2040	2040	2040
Sweden	Forsmark 2	1,120	1981	2040	2040	2040	2040
Sweden	Forsmark 3	1,187	1985	2045	2045	2045	2045
Sweden	site 1	1,300		cancelled	2050	2045	2040
Sweden	site 2	1,300		cancelled	2045	2040	2040
SE TOTAL 2015		8,376					
	Sweden Nucler Power Lever Sparklines, 2015-2050						

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Switzerland	Beznau 1	365	1969	2020	2020	2025	2030
Switzerland	Beznau 2	365	1971	2020	2020	2025	2030
Switzerland	Gösgen	1,010	1979	2025	2025	2025	2025
Switzerland	Mühleberg	373	1971	2015	2015	2015	2015
Switzerland	Leibstadt	1,220	1984	2025	2030	2030	2030
CH TOTAL 2015		3,333					
	Switzerland Nucler Power Lever Sparklines, 2015-2050						

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
UK	Dungeness B 1&2	1,040	1985	2025	2025	2025	2025
UK	Hartlepool 1&2	1,180	1984	2020	2020	2020	2020
UK	Heysham I 1&2	1,155	1984	2020	2020	2020	2020
UK	Heysham II 1&2	1,220	1988	2030	2030	2030	2050
UK	Hinkley Point B 1&2	945	1976	2020	2020	2020	2020
UK	Hunterston B 1&2	960	1977	2020	2020	2020	2020
UK	Torness 1&2	1,185	1989	2030	2030	2030	2050
UK	Sizewell B	1,198	1995	2035	2035	2035	2050
UK	Hinkley Point C1	1,670		2035	2035	2025	2025
UK	Hinkley Point C2	1,670		2035	2035	2025	2025
UK	Sizewell C1	1,670		cancelled	2035	2025	2025
UK	Sizewell C2	1,670		cancelled	2035	2025	2025
UK	Wylfa Newydd 1	1,380		2035	2035	2025	2025
UK	Wylfa Newydd 2	1,380		2035	2035	2025	2025
UK	Oldbury B1	1,380		cancelled	2040	2030	2030
UK	Oldbury B2	1,380		cancelled	2040	2030	2030
UK	Moorside 1	1,135		cancelled	2040	2030	2030
UK	Moorside 2	1,135		cancelled	2040	2030	2030
UK	Moorside 3	1,135		cancelled	2040	2030	2030
UK	Bradwell B1	1,150		cancelled	2045	2035	2035
UK	Bradwell B2	1,150		cancelled	2045	2035	2035
UK TOTAL 2015		8,883					
United Kingdom Nucler Power Lever Sparklines, 2015-2050							

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10.3 Coal phase-out policies of countries

The table shows the coal policies per countries as of 2018. These policies had been considered when defining the ambition levels per countries.

	Coal policy	Capacities in 2015?	New capacities?	Levels defined?	Source
AT	phase-out by 2025, last coal power plant is announced to close in 2020	YES	NO	NO	link
BE	last coal power plant closed in 2016	YES	NO	NO	
BG	no phase-out	YES	NO	YES	
HR	no phase-out	YES	NO	YES	
CY	no phase-out	YES	NO	YES	
CZ	aiming to close coal mines	YES	NO	YES	link
DK	phase-out by 2030	YES	NO	YES	link
EE	no coal	NO	NO	NO	
FI	phase-out by 2025/2030	YES	NO	YES	link
FR	phase-out by 2021	YES	NO	YES	link
DE	phase-out under discussion	YES	YES	YES	link
GR	no phase-out	YES	YES	YES	
HU	no phase-out	YES	YES	YES	
IE	phase-out by 2025	YES	NO	YES	link
IT	phase-out by 2025	YES	NO	YES	link
LV	no coal	NO	NO	NO	
LT	no coal	NO	NO	NO	
LU	no coal	NO	NO	NO	
MT	no coal	NO	NO	NO	
NL	phase-out by 2030	YES	NO	YES	link
PL	no phase-out	YES	YES	YES	
PT	phase-out by 2030	YES	NO	YES	link
RO	no phase-out	YES	YES	YES	
SK	phase-out under discussion by 2023	YES	NO	YES	link
SI	no phase-out	YES	NO	YES	
SP	no phase-out	YES	NO	YES	
SE	phase-out by 2022	YES	NO	YES	link
CH	no coal	NO	NO	NO	
UK	phase-out by 2025	YES	NO	YES	link

10.4 Details of bottom-up, power plant based coal power ambition levels

Based on the above policies and the coal power plant databases[12], the levels were defined for indicated countries in the above table.

The below tables list the operational coal power plants in 2015 as extracted from the above databases, as well as new plants in different phases of development in yellow fields. For plants the actual or proposed capacity values are listed and for operating plants in 2015 the commission date. Power plants marked by * closed between 2015 and 2020, thus are not considered in any levels. For each power plant, four possible dates are indicated as closing year. Proposed new plants are only included in level 4. Per power plant the dates can be the same, however, if aggregating the dates to get the levels, those differ aligned to the general level definitions.

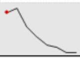
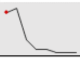
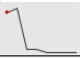
Bottom of the table, sparklines show trends of capacity changes by level with red dot for the 2015 value, and zero as minimal value. Maximum value depends on country, and chosen as the highest potential capacity level across ambitions, thus for a country each sparkline has the same maximum value set.

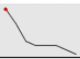
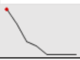
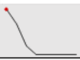
There is a difference observed between the 2015 value from the historical database of JRC-IDEES and the sum of bottom-up method. In order to make data series coherent, values in future time series were corrected by the ratio of 2015 historical gross values (JRC-IDEES) and 2015 value as extracted and summed from the different databases.

[12]Climate Analytics: Coal Phase Out in the EU - Detailed Information http://climateanalytics.org/briefings/eu-coal-phase-out/eu-coal-phase-out-detailed-information.html,
Global Coal Power Plant Tracker https://endcoal.org/tracker/,
European Coal Map by CAN Europe pdf version downloaded from http://coalmap.eu/#/,
Europe Beyond Coal webpage https://beyond-coal.eu/

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Bulgaria	AES Galabovo	600	2011	2050	2045	2035	2025
Bulgaria	Bobov Dol	580	1973	2025	2025	2020	2020
Bulgaria	Brikel	184	1975	2025	2025	2025	2020
Bulgaria	Deven	791	2009	2050	2045	2035	2025
Bulgaria	Maritsa 3	100	1971	2020	2020	2020	2020
Bulgaria	Maritsa East 2 unit 1	177	1966	2020	2020	2020	2020
Bulgaria	Maritsa East 2 unit 2	165	1967	2020	2020	2020	2020
Bulgaria	Maritsa East 2 unit 3	177	1967	2020	2020	2020	2020
Bulgaria	Maritsa East 2 unit 4	177	1968	2020	2020	2020	2020
Bulgaria	Maritsa East 2 unit 5	210	1985	2035	2025	2020	2020
Bulgaria	Maritsa East 2 unit 6	232	1985	2035	2025	2020	2020
Bulgaria	Maritsa East 2 unit 7	232	1990	2040	2030	2025	2020
Bulgaria	Maritsa East 2 unit 8	232	1995	2045	2030	2025	2020
Bulgaria	Maritsa East 3 unit 1	227	1978	2025	2025	2020	2020
Bulgaria	Maritsa East 3 unit 2	227	1979	2025	2025	2025	2020
Bulgaria	Maritsa East 3 unit 3	227	1980	2030	2030	2025	2020
Bulgaria	Maritsa East 3 unit 4	227	1981	2030	2030	2025	2020
Bulgaria	Republika	105	1975	2025	2025	2020	2020
Bulgaria	Ruse Iztok unit 1	30	1964	2020	2020	2020	2020
Bulgaria	Ruse Iztok unit 2	30	1964	2020	2020	2020	2020
Bulgaria	Ruse Iztok unit 3	110	1966	2020	2020	2020	2020
Bulgaria	Ruse Iztok unit 4	110	1971	2020	2020	2020	2020
Bulgaria	Ruse Iztok unit 5	60	1985	2035	2030	2025	2020
Bulgaria	Ruse Iztok unit 6	60	1985	2035	2030	2025	2020
Bulgaria	Sliven	28	1969	2020	2020	2020	2020
Bulgaria	Vidin	120	1970	2020	2020	2020	2020
BG TOTAL 2015		5,418					
Bulgaria Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Croatia	Plomin A	115	1969	2015	2015	2015	2015
Croatia	Plomin B	193	2000	2050	2035	2025	2020
HR TOTAL 2015		308					
Croatia Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Czech Republic	Brno 1 & 2	72	1984	2030	2030	2020	2020
Czech Republic	Budejovice	27	1971	2020	2020	2020	2020
Czech Republic	Chvaletice	736	1979	2025	2025	2020	2020
Czech Republic	Detmarovice	736	1976	2025	2025	2020	2020
Czech Republic	Frydek-Mistek Arcelor	26	1963	2020	2020	2020	2020
Czech Republic	Frydek-Mistek Dalkia	62	1975	2025	2025	2020	2020
Czech Republic	Hodonin	92	1957	2020	2020	2020	2020
Czech Republic	Karvina	28	1975	2025	2025	2020	2020
Czech Republic	Kladno 3	135	2014	2050	2040	2025	2025
Czech Republic	Kladno 4	135	2000	2050	2040	2025	2020
Czech Republic	Kladno 5	135	2000	2050	2040	2025	2020
Czech Republic	Krnov	43	1975	2025	2025	2025	2020
Czech Republic	Ledvice II	110	1969	2020	2020	2020	2020
Czech Republic	Ledvice III	110	1969	2020	2020	2020	2020
Czech Republic	Ledvice IV	110	1969	2020	2020	2020	2020
Czech Republic	Ledvice VI (constructio	660	2015	2050	2040	2035	2030
Czech Republic	Malesice	101	1965	2020	2020	2020	2020
Czech Republic	Melnik I	324	1960	2020	2020	2020	2020
Czech Republic	Melnik II	202	1971	2020	2020	2020	2020
Czech Republic	Melnik III	460	1981	2030	2030	2020	2020
Czech Republic	Olomouc	38	1952	2020	2020	2020	2020
Czech Republic	Opatovice	110	1960	2020	2020	2020	2020
Czech Republic	Ostrov	32	1975	2020	2020	2020	2020
Czech Republic	Otrokovice	46	1970	2020	2020	2020	2020
Czech Republic	Plana	43	1961	2020	2020	2020	2020
Czech Republic	Plzen 1	70	1980	2030	2030	2020	2020
Czech Republic	Plzen 2	67	1995	2045	2040	2025	2020
Czech Republic	Plzenska (Skoda) 1	32	1960	2020	2020	2020	2020
Czech Republic	Plzenska (Skoda) 2	33	1984	2030	2030	2020	2020
Czech Republic	Pocerady I	552	1971	2020	2020	2020	2020
Czech Republic	Pocerady II	368	1977	2025	2025	2020	2020
Czech Republic	Porici II	152	1957	2020	2020	2020	2020
Czech Republic	Prerov	56	1966	2020	2020	2020	2020
Czech Republic	Prunerov 1	405	1968	2020	2020	2020	2020
Czech Republic	Prunerov II	966	1982	2030	2030	2025	2020
Czech Republic	Tisova I	158	1958	2020	2020	2020	2020
Czech Republic	Tisova II	95	1962	2020	2020	2020	2020
Czech Republic	Trebovice	155	1952	2020	2020	2020	2020
Czech Republic	Tusimice	751	1974	2020	2020	2020	2020
Czech Republic	Usti nad Labem	81	1984	2030	2030	2020	2020
Czech Republic	Varnsdorf	22	2004	2050	2040	2025	2025
Czech Republic	Zlin	61	1996	2050	2040	2025	2020
CZ TOTAL 2015		7,937					
Czech Republic Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Denmark	Amager*	263	1989	2015	2015	2015	2015
Denmark	Asnaes	1,057	1962	2020	2020	2020	2020
Denmark	Avedore*	241	1990	2015	2015	2015	2015
Denmark	Esbjerg	407	1992	2020	2020	2020	2020
Denmark	Fyns	362	1991	2040	2030	2025	2020
Denmark	Nordjylland unit 2	305	1977	2025	2025	2020	2020
Denmark	Nordjylland unit 3	411	1998	2045	2030	2025	2020
Denmark	Ostkraft*	34	1995	2015	2015	2015	2015
Denmark	Studstrup*	690	1984	2015	2015	2015	2015
DK TOTAL 2015		3,770					
Denmark Coal Power Lever Sparklines, 2015-2050							

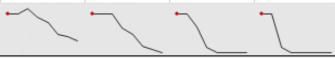
Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Finland	Hanasaari B	210	1974	2020	2020	2020	2020
Finland	Heinola	39	1984	2030	2025	2020	2020
Finland	Kristiina*	244	1983	2015	2015	2015	2015
Finland	Kuopio	60	1972	2020	2020	2020	2020
Finland	Kymenso	50	1971	2020	2020	2020	2020
Finland	Kymijarvi*	127	1982	2015	2015	2015	2015
Finland	Martinlaakso	80	1980	2035	2030	2025	2020
Finland	Meri-Pori	614	1994	2040	2030	2025	2020
Finland	Naantali-1	366	1960	2025	2025	2025	2020
Finland	Pargas	30	1958	2020	2020	2020	2020
Finland	Salmissari	177	1984	2030	2025	2025	2020
Finland	Suomenoja	170	1977	2025	2025	2025	2020
Finland	Tahkoluoto (Pori)*	232	1976	2015	2015	2015	2015
Finland	Vaskiluoto	250	1981	2035	2030	2025	2020
FI TOTAL 2015		2,649					
Finland Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
France	Bois-Rouge unit 1	62	1992	2040	2030	2025	2020
France	Bois-Rouge unit 2	46	2004	2050	2030	2025	2020
France	Cordemais	1,104	1983	2030	2030	2025	2020
France	Emile-Houchet	595	1981	2030	2030	2025	2020
France	Le Gol 1	64	1995	2045	2030	2025	2020
France	Le Gol 2	58	2006	2050	2030	2025	2020
France	Le Havre II	600	1983	2030	2030	2025	2020
France	Provence	595	1984	2030	2030	2025	2020
FR TOTAL 2015		3,124					
France Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Germany	Altbach/Deizisau	769	1985	2020	2020	2025	2020
Germany	Bergkamen	717	1981	2030	2030	2020	2020
Germany	Berlin-Moabit*	89	1990	2030	2030	2020	2015
Germany	Berlin-Reuter	124	1969	2020	2020	2020	2020
Germany	Berlin-Reuter West	564	1987	2030	2030	2025	2025
Germany	Bexbach	721	1983	2015	2015	2015	2020
Germany	Boxberg unit N	500	1979	2040	2040	2020	2020
Germany	Boxberg unit P	500	1980	2040	2040	2020	2020
Germany	Boxberg unit Q	907	2000	2040	2040	2030	2025
Germany	Boxberg R (unit)	675	2012	2040	2040	2030	2025
Germany	Bremen-Farge	350	1969	2020	2020	2020	2020
Germany	Bremen-Hafen 6	300	1979	2025	2025	2025	2025
Germany	Bremen-Hastedt	119	1989	2035	2035	2025	2025
Germany	Buer	76	1985	2035	2035	2025	2025
Germany	Chemnitz North II	148	1988	2025	2025	2025	2020
Germany	Cottbus	74	1999	2045	2045	2020	2020
Germany	Datteln	1,052	2018	2050	2050	2025	2025
Germany	Dessau*	49	1996	2050	2050	2015	2015
Germany	Dortmund G Knepper	345	1971	2015	2015	2015	2020
Germany	Duisburg-Hochfeld II*	95	1985	2015	2015	2015	2015
Germany	Duisburg-Walsum 10	790	2013	2050	2050	2030	2025
Germany	Duisburg-Walsum 9	410	1988	2035	2035	2025	2025
Germany	Ensdorf*	389	1963	2020	2020	2020	2015
Germany	Erlangen	17	1980	2030	2030	2020	2020
Germany	E-Weisweiler E	363	1965	2030	2030	2015	2020
Germany	E-Weisweiler F	340	1967	2030	2030	2020	2020
Germany	E-Weisweiler G	630	1974	2030	2030	2015	2020
Germany	E-Weisweiler H	625	1975	2030	2030	2015	2020
Germany	Flensburg	147	1978	2025	2025	2025	2025
Germany	Frankfurt/Main West	62	1989	2035	2035	2025	2025
Germany	Frankfurt/Oder	45	1997	2045	2045	2025	2025
Germany	G Staudinger	510	1992	2020	2020	2025	2020
Germany	G-Frimmersdorf	562	1966	2015	2015	2015	2020
Germany	G-Neurath A	294	1972	2020	2020	2020	2020
Germany	G-Neurath B	294	1972	2020	2020	2020	2020
Germany	G-Neurath C	292	1973	2015	2015	2015	2020
Germany	G-Neurath D	607	1975	2015	2015	2015	2020
Germany	G-Neurath E	604	1976	2015	2015	2015	2020
Germany	G-Neurath F	1,060	2012	2050	2050	2030	2025
Germany	G-Neurath G	1,060	2012	2050	2050	2030	2025
Germany	Hamburg-Moorburg 1	792	2014	2050	2050	2030	2025
Germany	Hamburg-Moorburg 2	792	2014	2050	2050	2030	2025
Germany	Hamburg-Tiefstack	194	1993	2040	2040	2030	2025
Germany	Hamm Westfalen	993	1969	2015	2015	2015	2020
Germany	Hamm Westfalen E	800	2014	2050	2050	2030	2025
Germany	Hannover	272	1989	2035	2035	2025	2025
Germany	Heilbronn unit 7	778	1985	2020	2020	2025	2020
Germany	Helmstedt Buschhaus*	352	1985	2015	2015	2015	2015
Germany	Herne 3	229	1966	2015	2015	2015	2020
Germany	Herne 4	500	1989	2035	2035	2025	2020
Germany	Ibbenbueren	794	1985	2035	2035	2020	2020
Germany	Jaenschwalde A	465	1981	2030	2030	2020	2020
Germany	Jaenschwalde B	465	1982	2030	2030	2025	2020
Germany	Jaenschwalde C	465	1984	2030	2030	2025	2020
Germany	Jaenschwalde D	465	1985	2030	2030	2025	2020
Germany	Jaenschwalde E	465	1987	2015	2015	2015	2020
Germany	Jaenschwalde F	465	1989	2015	2015	2015	2020
Germany	Karlsruhe	1,344	1985	2020	2020	2025	2020
Germany	Kassel	34	1988	2035	2035	2025	2020
Germany	Lippendorf	1,750	1999	2045	2045	2025	2025

(continued next page)

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Germany	Luenen*	473	1962	2015	2015	2020	2015
Germany	Luenen-Stummhafen	746	2013	2050	2050	2030	2025
Germany	Mannheim 6	280	1975	2025	2025	2015	2020
Germany	Mannheim 7	475	1982	2030	2030	2025	2025
Germany	Mannheim 8	480	1993	2040	2040	2025	2025
Germany	Mannheim 9	912	2014	2050	2050	2030	2030
Germany	Marl 5	75	1983	2030	2030	2025	2025
Germany	Marl 3	68	1966	2020	2020	2020	2020
Germany	Mehrum	690	1979	2025	2025	2020	2020
Germany	Munich North	333	1991	2035	2035	2025	2025
Germany	Niederaussem C	335	1965	2020	2020	2020	2020
Germany	Niederaussem D	320	1968	2020	2020	2020	2020
Germany	Niederaussem E	315	1970	2015	2015	2020	2020
Germany	Niederaussem F	320	1971	2015	2015	2020	2020
Germany	Niederaussem G	687	1974	2020	2020	2020	2020
Germany	Niederaussem H	687	1974	2020	2020	2020	2020
Germany	Niederaussem K	1,012	2002	2050	2050	2030	2025
Germany	Offenbach	54	1990	2040	2040	2025	2025
Germany	Petershagen Heyden	875	1987	2035	2035	2025	2025
Germany	Pforzheim	27	1990	2040	2040	2025	2025
Germany	Quierschied-Weiher	656	1976	2015	2015	2025	2020
Germany	Rostock	508	1994	2040	2040	2025	2025
Germany	S Roemerbruecke	50	1988	2035	2035	2025	2025
Germany	Schkopau	900	1996	2045	2045	2025	2025
Germany	Scholven	740	1968	2020	2020	2020	2020
Germany	Schwarze Pumpe	1,500	1997	2045	2045	2025	2025
Germany	Stuttgart-Gaisburg*	23	2009	2015	2015	2015	2015
Germany	Stuttgart-Muenster	89	1982	2030	2030	2025	2020
Germany	Voelklingen-Fenne	390	1982	2030	2030	2025	2025
Germany	Voerde*	1,390	1982	2015	2015	2015	2015
Germany	Voerde West*	640	1971	2015	2015	2015	2015
Germany	Waehlitz	31	1994	2040	2040	2030	2025
Germany	Walheim	244	1964	2015	2015	2020	2020
Germany	Wedel	260	1961	2020	2020	2020	2020
Germany	Werdohl-Elverlingsen*	310	1982	2015	2015	2025	2015
Germany	Werne Gersteinwerk*	608	1984	2015	2015	2015	2015
Germany	Wilhelmshaven	757	1976	2025	2025	2015	2020
Germany	Wilhelmshaven E	731	2015	2050	2050	2030	2025
Germany	Wolfsburg North	123	2000	2050	2050	2025	2025
Germany	Wolfsburg West	277	1985	2035	2035	2025	2025
Germany	Wuppertal-Elberfeld*	85	1989	2015	2015	2015	2015
Germany	Zolling-Leininger	472	1986	2035	2035	2025	2020
Germany	pre-permit	2,000		2030	cancelled	cancelled	cancelled
DE TOTAL 2015		47,854					
Germany Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Greece	Agios Dimitrios 1	300	1984	2030	2030	2025	2020
Greece	Agios Dimitrios 2	300	1984	2030	2030	2025	2020
Greece	Agios Dimitrios 3	310	1985	2035	2035	2025	2020
Greece	Agios Dimitrios 4	310	1986	2035	2035	2025	2020
Greece	Agios Dimitrios 5	375	1997	2045	2045	2030	2025
Greece	Kardia	1,110	1975	2025	2025	2020	2020
Greece	Amintaio	546	1987	2035	2035	2025	2020
Greece	Melitis (Florina)	289	2003	2050	2050	2030	2025
Greece	Megalopoli A unit 3	300	1975	2025	2025	2020	2020
Greece	Megalopoli A unit 4	300	1991	2040	2040	2025	2020
Greece	Ptolemaida (const)	600		2025	cancelled	cancelled	cancelled
Greece	Meliti-II (announced)	450		2030	cancelled	cancelled	cancelled
GR TOTAL 2015		4,140					
Greece Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Hungary	Mátra	769	1969	2030	2030	2025	2020
Hungary	Oroszlány	230	1961	2020	2020	2020	2020
Hungary	Bakony	95	1957	2020	2020	2020	2020
Hungary	Mátra 6 (pre-permit)	500		2030	cancelled	cancelled	cancelled
HU TOTAL 2015		1,094					
			Hungary Coal Power Lever Sparklines, 2015-2050				

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Ireland	Moneypoint	842	1985	2035	2030	2025	2020
IE TOTAL 2015		842					
			Ireland Coal Power Lever Sparklines, 2015-2050				

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Italy	Bastardo (P Vannucci)	138	1990	2040	2050	2025	2020
Italy	Brescia	69	1988	2040	2030	2025	2020
Italy	Brindisi Nord	589	1970	2050	2030	2020	2020
Italy	Brindisi Sud	2,429	1991	2020	2020	2025	2020
Italy	Fiume Santo	598	1992	2040	2030	2025	2020
Italy	Fusina 1 (A Palladio)	165	1964	2040	2030	2020	2020
Italy	Fusina 2 (A Palladio pov	171	1969	2020	2020	2020	2020
Italy	Fusina 3 (A Palladio pov	320	1974	2020	2020	2025	2020
Italy	Fusina 4 (A Palladio pov	320	1974	2030	2030	2025	2020
Italy	Genova*	271	1952	2030	2030	2015	2015
Italy	La Spezia	552	1967	2015	2015	2020	2020
Italy	Marghera	129	1977	2020	2020	2025	2020
Italy	Monfalcone	309	1965	2030	2030	2020	2020
Italy	Sulcis	534	1986	2020	2020	2025	2020
Italy	Torrevaldaliga N 1	660	2009	2035	2030	2025	2020
Italy	Torrevaldaliga N 2	660	2010	2050	2030	2025	2020
Italy	Torrevaldaliga N 3	660	2010	2050	2030	2025	2020
IT TOTAL 2015		8,574					
			Italy Coal Power Lever Sparklines, 2015-2050				

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Netherlands	Amer 8	701	1981	2015	2015	2015	2015
Netherlands	Amer 9	652	1994	2040	2030	2025	2020
Netherlands	Borssele 12*	406	1988	2015	2015	2015	2015
Netherlands	Eemshaven	1,600	2014	2050	2030	2025	2020
Netherlands	Gelderland 13*	602	1982	2015	2015	2015	2015
Netherlands	Hemweg*	630	1995	2015	2015	2015	2015
Netherlands	Maasvlakte*	1,040	1988	2015	2015	2015	2015
Netherlands	Maasvlakte 3 (test)	1,070	2015	2050	2030	2025	2020
Netherlands	Maasvlakte Engie	800	2014	2050	2030	2025	2020
NL TOTAL 2015		6,431					
			Netherlands Coal Power Lever Sparklines, 2015-2050				

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Poland	Adamow*	552	1964	2020	2020	2020	2020
Poland	Bedzin	78	1975	2025	2025	2020	2020
Poland	Belchatow	4,016	1981	2030	2030	2020	2020
Poland	Belchatow II	858	2011	2050	2050	2025	2025
Poland	Bialystok	92	1978	2025	2025	2025	2020
Poland	Bielsko-Biala	46	2010	2050	2050	2025	2025
Poland	Blachownia*	107	1957	2020	2020	2020	2020
Poland	Bydgoszcz II unit 1	55	1971	2020	2020	2020	2020
Poland	Bydgoszcz II unit 2	32	1971	2020	2020	2020	2020
Poland	Bydgoszcz II unit 3	55	1976	2025	2025	2020	2020
Poland	Bydgoszcz II unit 4	50	1984	2030	2030	2025	2020
Poland	Chorzow 2	202	2000	2050	2050	2025	2025
Poland	Czestochowa	59	2010	2050	2050	2020	2020
Poland	Dolna Odra	1,187	1974	2025	2025	2025	2020
Poland	Gdansk 2	195	1970	2025	2025	2025	2020
Poland	Gdynia	97	1980	2030	2030	2025	2025
Poland	Jaworzno 2	184	1998	2050	2050	2025	2025
Poland	Jaworzno 3	1,237	1977	2025	2025	2020	2020
Poland	Jaworzno 3 B7	910	2015	2050	2050	2025	2025
Poland	Katowice	124	1995	2045	2045	2025	2025
Poland	Konin	182	1958	2020	2020	2020	2020
Poland	Kozienice 1	215	1972	2020	2020	2020	2020
Poland	Kozienice 2	225	1973	2020	2020	2020	2020
Poland	Kozienice 3	225	1973	2020	2020	2020	2020
Poland	Kozienice 4	228	1973	2020	2020	2020	2020
Poland	Kozienice 5	225	1973	2020	2020	2020	2020
Poland	Kozienice 6	228	1974	2020	2020	2020	2020
Poland	Kozienice 7	225	1974	2020	2020	2020	2020
Poland	Kozienice 8	228	1975	2020	2020	2020	2020
Poland	Kozienice 9	560	1978	2025	2025	2020	2020
Poland	Kozienice 10	560	1979	2025	2025	2020	2020
Poland	Kozienice B11	1,075	2015	2050	2050	2050	2030
Poland	Krakow 1	120	1970	2020	2020	2020	2020
Poland	Krakow 2	120	1975	2025	2025	2020	2020
Poland	Krakow 3	110	1985	2035	2035	2020	2020
Poland	Krakow 4*	110	1985	2020	2020	2020	2020
Poland	Lagisza 6	120	1963	2020	2020	2020	2020
Poland	Lagisza 7	120	1970	2020	2020	2020	2020
Poland	Lagisza 8	460	2009	2050	2050	2025	2020
Poland	Laziska 1	125	1960	2020	2020	2020	2020
Poland	Laziska 2	125	1960	2020	2020	2020	2020
Poland	Laziska 9	230	1971	2020	2020	2025	2020
Poland	Laziska 10	225	1971	2020	2020	2025	2020
Poland	Laziska 11	225	1972	2020	2020	2025	2020
Poland	Laziska 12	225	1972	2020	2020	2025	2020
Poland	Lodz 3	182	1968	2020	2020	2020	2020
Poland	Lodz 4 unit 1	55	1977	2025	2025	2020	2020
Poland	Lodz 4 unit 2	55	1978	2025	2025	2020	2020
Poland	Lodz 4 unit 3	105	1992	2040	2040	2025	2020
Poland	Miechowice	115	1955	2020	2020	2020	2020
Poland	Opole 1	386	1993	2040	2040	2025	2020
Poland	Opole 2	383	1994	2040	2040	2025	2020
Poland	Opole 3	383	1996	2045	2045	2025	2025
Poland	Opole 4	380	1997	2045	2045	2025	2025
Poland	Opole 5	900	2015	2050	2050	2050	2030
Poland	Opole 6	900	2015	2050	2050	2050	2030
Poland	Ostroleka A	86	1956	2020	2020	2020	2020
Poland	Ostroleka B	595	1972	2020	2020	2020	2020
Poland	Patnow I	1,104	1965	2020	2020	2020	2020
Poland	Patnow II	442	2008	2050	2050	2025	2020

(continued next page)

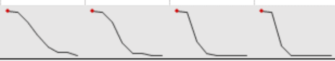
Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Poland	Polaniec	1,449	1979	2025	2025	2020	2020
Poland	Pomorzany	110	1959	2020	2020	2020	2020
Poland	Poznan-Karolin	270	1985	2035	2035	2025	2020
Poland	Rybnik 1	225	1972	2020	2020	2020	2020
Poland	Rybnik 2	225	1972	2020	2020	2020	2020
Poland	Rybnik 3	225	1973	2020	2020	2020	2020
Poland	Rybnik 4	225	1974	2020	2020	2020	2020
Poland	Rybnik 5	215	1978	2025	2025	2020	2020
Poland	Rybnik 6	215	1978	2025	2025	2020	2020
Poland	Rybnik 7	220	1978	2025	2025	2020	2020
Poland	Rybnik 8	225	1978	2025	2025	2020	2020
Poland	Siekierki	569	1961	2020	2020	2020	2020
Poland	Siersza 1	153	2002	2050	2050	2025	2020
Poland	Siersza 2	153	2002	2050	2050	2025	2020
Poland	Siersza 3	123	1955	2020	2020	2020	2020
Poland	Siersza 6	128	1969	2020	2020	2020	2020
Poland	Skawina	405	1970	2020	2020	2020	2020
Poland	Stalowa Wola	230	1958	2020	2020	2020	2020
Poland	Turow	1,201	1962	2020	2020	2020	2020
Poland	Turow unit 11	460	2015	2050	2050	2050	2030
Poland	Tychy	87	2003	2050	2050	2025	2020
Poland	Wroclaw	235	1970	2020	2020	2020	2020
Poland	Zabrze	98	1985	2030	2030	2020	2020
Poland	Zabrze II	75	2015	2050	2050	2050	2030
Poland	Zeran 9	386	2005	2050	2050	2020	2020
Poland	Zeran 11	100	1965	2020	2020	2020	2020
Poland	Zeran 12	100	2009	2050	2050	2025	2020
Poland	Zofiowka*	59	1974	2020	2020	2020	2020
Poland	Z Moszczenica	37	1966	2020	2020	2020	2020
Poland	pre-permit	2,600		2025	cancelled	cancelled	cancelled
Poland	announced	3,100		2030	cancelled	cancelled	cancelled
PL TOTAL 2015		26,581					
	Poland Coal Power Lever Sparklines, 2015-2050						

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Portugal	Pego	682	1995	2045	2030	2025	2020
Portugal	Sines	1,296	1987	2035	2030	2025	2020
PT TOTAL 2015		1,978					
	Portugal Coal Power Lever Sparklines, 2015-2050						

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Romania	Arad II	50	1993	2040	2040	2025	2020
Romania	Brasov*	50	1995	2015	2015	2015	2015
Romania	Craiova II	122	1987	2035	2035	2025	2020
Romania	Doicesti*	184	1980	2015	2015	2015	2015
Romania	Drobeta*	120	1986	2015	2015	2015	2015
Romania	Giurgiu*	92	1984	2015	2015	2015	2015
Romania	Govora	82	1986	2035	2035	2025	2020
Romania	Iasi II	43	1986	2035	2035	2025	2020
Romania	Isalnita	572	1987	2035	2035	2025	2020
Romania	Mintia	930	1975	2025	2025	2025	2020
Romania	Oradea II*	134	1967	2015	2015	2015	2015
Romania	Paroseni	150	1964	2020	2020	2020	2020
Romania	Rovinari	1,166	1976	2025	2025	2025	2020
Romania	Turceni	1,198	1983	2030	2030	2025	2020
Romania	Rovinari 7 pre-permit	600		2025	cancelled	cancelled	cancelled
RO TOTAL 2015		4,893					
	Romania Nucler Power Lever Sparklines, 2015-2050						

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Slovakia	Martinska	39	1975	2025	2025	2025	2020
Slovakia	Novaky ENO A	72	1957	2020	2020	2020	2020
Slovakia	Novaky ENO B	202	1964	2020	2020	2020	2020
Slovakia	Teko (Kosice)	111	1967	2020	2020	2020	2020
Slovakia	Vojany I	405	1965	2020	2020	2020	2020
Slovakia	Sal'A Plant	46	2004	2050	2035	2025	2020
Slovakia	Sturovo 1	50	1986	2035	2030	2020	2020
Slovakia	US Steel Kosice	192	2004	2050	2035	2025	2020
SK TOTAL 2015		1,117					
Slovakia Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Slovenia	Sostanj 4	275	1968	2015	2015	2015	2015
Slovenia	Sostanj 5	345	1977	2025	2025	2025	2020
Slovenia	Sostanj 6	600	2015	2050	2045	2035	2025
Slovenia	Te-Tol 1	42	1966	2020	2015	2015	2015
Slovenia	Te-Tol 2	32	1967	2020	2015	2015	2015
Slovenia	Te-Tol 3	50	1984	2030	2030	2025	2020
SI TOTAL 2015		744					
Slovenia Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Spain	Abono 1	360	1974	2020	2020	2020	2020
Spain	Abono 2	556	1985	2035	2030	2025	2025
Spain	Alcudia II 1	125	1981	2030	2030	2020	2020
Spain	Alcudia II 2	125	1982	2030	2030	2020	2020
Spain	Alcudia II 3	130	1997	2045	2030	2025	2020
Spain	Alcudia II 4	130	1997	2045	2030	2025	2020
Spain	Andorra (Teruel)	966	1979	2025	2025	2020	2020
Spain	Anllares*	336	1982	2015	2015	2015	2015
Spain	As Pontes	1,403	1976	2025	2025	2020	2020
Spain	Compostilla II	1,098	1965	2020	2020	2020	2020
Spain	La Robla 1	284	1971	2020	2020	2020	2020
Spain	La Robla 2	371	1984	2030	2030	2025	2020
Spain	Lada	329	1981	2030	2030	2020	2020
Spain	Litoral 1	577	1985	2030	2025	2025	2025
Spain	Litoral 2	582	1997	2045	2040	2030	2025
Spain	Los Barrios	570	1985	2035	2030	2025	2025
Spain	Meirama	509	1980	2030	2025	2020	2020
Spain	Narcea 1*	65	1965	2020	2020	2020	2020
Spain	Narcea 2	364	1969	2020	2020	2020	2020
Spain	Narcea 3	166	1984	2030	2025	2025	2020
Spain	Puente Nuevo	298	1980	2030	2025	2020	2020
Spain	Velilla	458	1964	2025	2025	2020	2020
SP TOTAL 2015		9,802					
Spain Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
Sweden	Vaesteras	138	1963	2020	2020	2020	2020
Sweden	Vaerta	105	1990	2040	2030	2025	2020
Sweden	Linkoeping	29	1964	2020	2020	2020	2020
SE TOTAL 2015		272					
Sweden Coal Power Lever Sparklines, 2015-2050							

Country	Name	Capacity (MW)	Start year	Last/first fifth year of operation			
				1	2	3	4
UK	Aberthaw	1,586	1971	2020	2020	2020	2020
UK	Cottam*	2,008	1969	2015	2015	2015	2015
UK	Drax unit 4-6	2,580	1976	2030	2025	2025	2020
UK	Eggborough*	1,960	1967	2015	2015	2015	2015
UK	Ferrybridge*	980	1966	2015	2015	2015	2015
UK	Fiddler's Ferry	1,471	1971	2020	2020	2020	2020
UK	Kilroot	520	1981	2020	2020	2020	2020
UK	Longannet*	2,260	1970	2015	2015	2015	2015
UK	Ratcliffe	1,500	1968	2025	2025	2020	2020
UK	Rugeley*	1,006	1972	2015	2015	2015	2015
UK	West Burton	2,012	1967	2025	2025	2020	2020
UK TOTAL 2015		17,883					
United Kingdom Coal Power Lever Sparklines, 2015-2050