Final Report
Cost of Energy (LCOE)

Energy costs, taxes and the impact of government interventions on investments

Trinomics

Contract details

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Study on energy costs, taxes and the impact of government interventions on investments in the energy sector ENER/2018-A4/2018-471

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Final Report - Cost of Energy (LCOE)

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CONTENTS

GLOSSARY

The levelised cost of energy (LCOE): is an indicator for the price of electricity or heat required for a project where the revenues would equal costs, including making a return on the capital invested equal to the discount rate. This study follows the same approach as IRENA (2018) for calculating a simple levelised cost of electricity/heat and applies it to electricity and/or heat generation plants. As a result, the LCOE indicator in this study will not consider taxes, subsidies or other incentives.

Investment costs (also referred to as CAPEX, or capital expenditures; also referred to as "overnight costs"): specific to the initial investment required for the set-up of a new energy producing system (power and/or heat plant). The overnight costs usually include the grid connection costs (onsite electrical equipment like switchyard and necessary upgrades at a transmission substation) except for offshore wind.

Operation and Maintenance costs (O&M; referred to as **OPEX, or operational expenditures)**: these expenditures include fixed and variable costs for operation and maintenance (except fuel costs). In this study, OPEX is specific to the O&M costs of electricity and heat generation systems.

The discount rate: reflects the average cost of capital as it is used to discount values back to the current/present year. It is important to highlight that actual financial conditions for CAPEX refunding may be very different from project to project leading to different LCOE results.

Capacity factor (also referred to as load factor): is the relation between how much electricity a plant produces and how much it would produce if it operated at full capacity 100% of the time. It is a measure of the amount of time a power plant produces in a year assuming it always produces at full load (equivalent full load hours), divided by the number of hours in a year.

ABBREVIATIONS

LCOE - Levelised cost of energy

IRENA - International Renewable Energy Agency

CCGT - Combined Cycle Gas Turbine

OCGT - Open Cycle Gas Turbine

IGCC - Integrated Gasification Combined Cycle (coal)

CHP - Combined Heat and Power

CSP - Concentrated Solar Power

CAPEX - Capital Expenditure

OPEX - Operational Expenditure

Plant IC - Plant Installed Capacity

RES – Renewable Energy Sources

FF – fossil fuel

EC – European Commission

ETS – Emissions Trading Scheme

Executive Summary

This report estimates the costs of producing electricity and heat from different technologies using the methodology of levelised cost of electricity and heat (LCOE&LCOH). The scope of this report includes all EU27 and non-EU G20 countries (including the UK). The timespan covered is: 2008, 2010, 2013, 2016, and 2018 for renewable energy sources and domestic[1] energy systems; and 2008, 2013, and 2018 for non-domestic thermal energy sources and nuclear. For results reporting, we present graphs using a discount rate of 3% for domestic systems and of 7% for all other technologies (large scale renewables, nuclear and thermal). Furthermore, all values (unless otherwise indicated) are in € of 2018 (real values). Investment costs used for LCOE estimates were overnight capital costs that already take into consideration costs related to the construction period of the power plants. Furthermore, LCOE results represent costs from the power plant's commissioning date and costs related to its operational lifetime (operational and fuel costs, when pertinent for the technology).

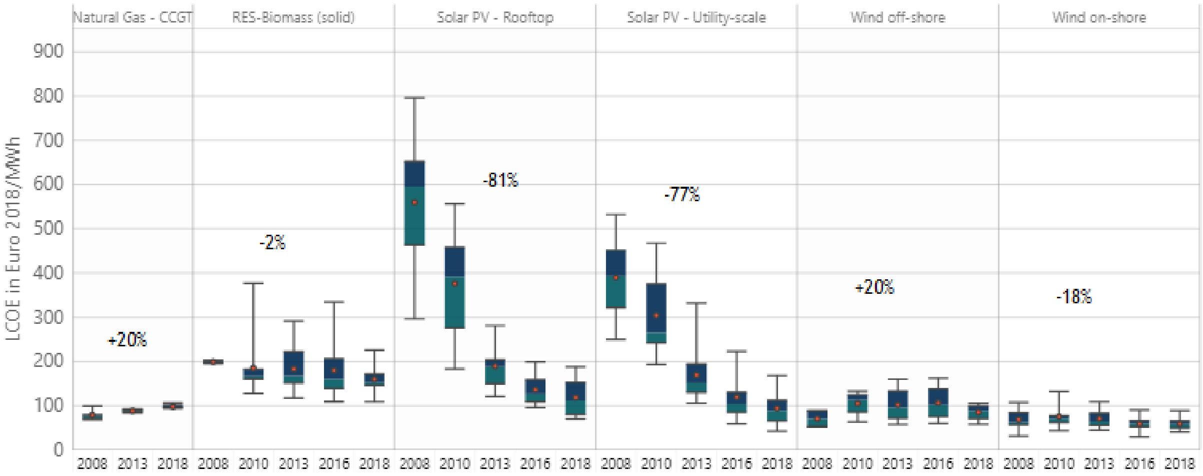
The database built is composed of almost 2 thousand observations[2], 22% is for wind onshore, 25% for solar PV and 8% for solid biomass. As expected, data for fossil fuel fired technologies (coal and gas) is less abundant due to a low number of projects in the period analysed (most projects, especially in EU27 countries, are older than 2008). Most data for LCOE calculation were provided by different data sources (experts submissions, IRENA, and Enerdata's Power Plant Tracker), but in some cases, estimations were needed. All methodology notes are detailed in Annex A.

LCOE results for new projects in EU27 show that most renewable energy sources (RES) have become cheaper than gas fired combined cycle gas turbines (CCGT) and supercritical coal power plants. In 2018 onshore wind LCOE were around €60/MWh, offshore wind around €85/MWh and utility-scale solar PV around €87/MWh. Meanwhile, despite the reduction of gas prices, LCOE of CCGT power plants have been around €95/MWh (20% higher than 2008 costs) while coal-fired power plants have costs around €90/MWh (12% higher than 2008 costs)[3]. Multiple aspects explain this: as the EU has established carbon prices, thermal generation costs increased. On the other hand, RES technology advancements and production in large scale drove capital expenditure (CAPEX) costs down significantly since 2008. As support schemes in most European countries have boosted the development of renewables, the large-scale production of solar PV panels/modules provided the "heated market" with cheap components, while the use of larger wind turbines (without significant increases in CAPEX) enabled power plants to access much higher capacity factors over time leading to lower LCOEs.

Nuclear power is not included in the EU27 summary results as no new plants have been commissioned in the EU27 since 2008. However, new plants in China, South Korea and the United States provide some basis for comparison with LCOEs ranging from €67/MWh in China to €82/MWh in the US in 2018.

[1] Domestic systems are energy systems installed at residential scale. The size of such systems is provided in detail within the database provided with this report.
[2] Each observation is the LCOE calculated using data provided by the sources (experts submissions, IRENA and Enerdata's PPT). The sources provide a mix of project specific information and national averages. Details are provided in the database provided with this report.
[3] It is important to mention that our sample for coal-fired power technologies is small due to the scarcity of new projects during the 2008-2018 period in the EU27.

Figure 0-1 LCOE results for EU27 - main technologies' comparison - percentage change between 2008 and 2018



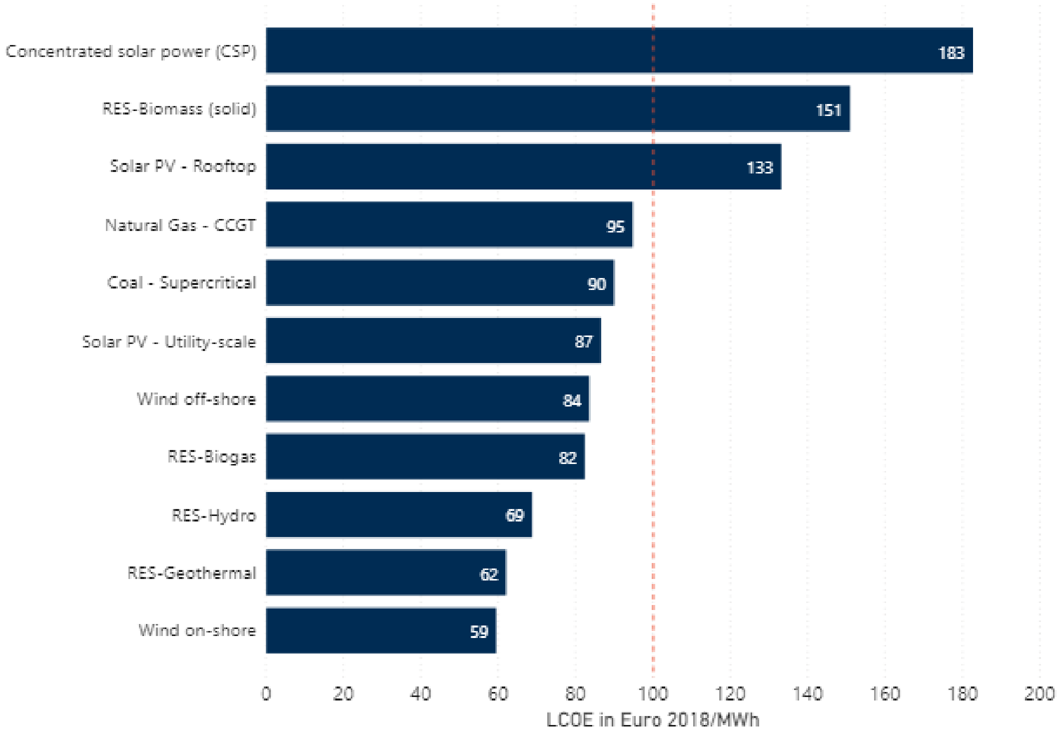
Number of observations per year

Country group	2008	2010	2013	2016	2018	Total
EU27	92	117	171	141	147	668

Source: Authors' elaboration.

Orange dot is the dataset's mean, lower whisker is the minimum while higher whisker is the maximum value observed. Boxes represent second and third quartiles.

Figure 0-2 LCOE results for EU27 - in 2018



Source: Authors' elaboration.

With a strong evolution of wind and solar, promising markets include China, the US and Europe in terms of market size.

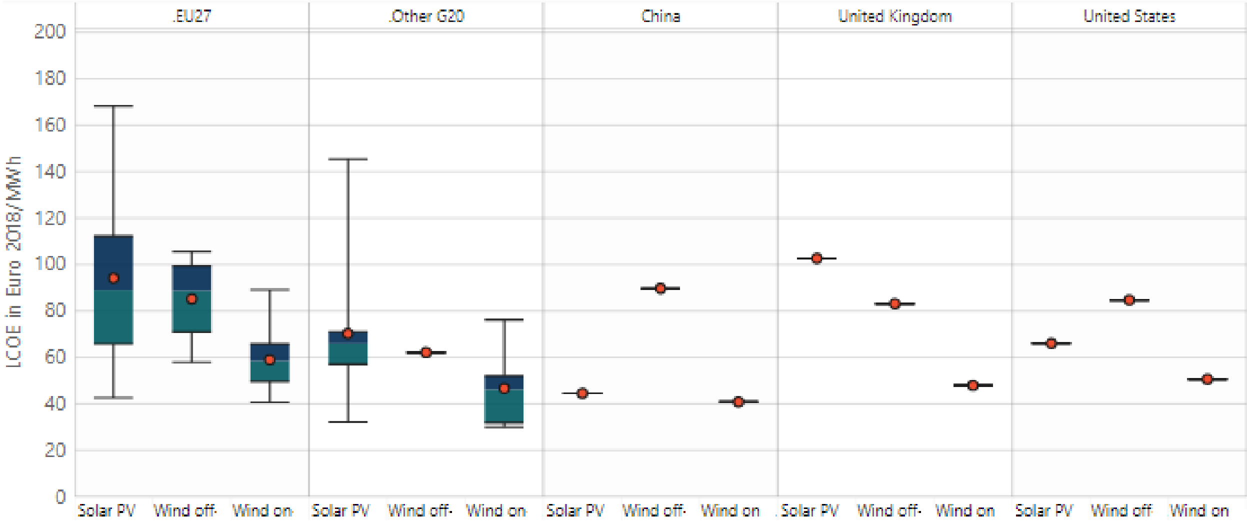
2018 CAPEX levels for **on-shore wind** in the US and the EU27 were €1,400/kW and €1,600/kW respectively, and average annual capacity factors were at 37% and 32%. These advantages in the American market are offset by higher O&M costs (at €40/kW/year whilst €30/kW/year in the EU27). With much lower soft costs (balance of plant, labour costs, etc.), the Chinese market presents a rather low LCOE for wind. In China, CAPEX for the technology were around €1,000/kW in 2018, while capacity factors remained around 30% and OPEX levels around €24/kW/year. Taking all these variables into account, LCOE in China is the lowest at €40/MWh in 2018, followed by the US at €50/MWh and Europe at €60/MWh.

With relatively low capacity additions of **off-shore wind** being registered over the 2008-2018 timeframe, and due to projects' specificities (location, distance from shore, depth of installations, etc.), LCOE for this technology show significant volatility in all countries. China presents the lowest CAPEX levels in 2018, around €2,200/kW, which is offset by relatively low recorded average annual capacity factors (around 30% in 2018). Meanwhile, the US and the European countries present more comparable CAPEX levels at €3,000/kW and €3,300/kW, respectively, and capacity factors between 45-50%.

For utility-scale **Solar PV** differences in LCOE results are explained by two aspects: national average annual capacity factors (based on the country's solar irradiation) and the level of "soft costs"[4] and installation within the CAPEX costs (IRENA 2019). In the US, those costs correspond to over 70% (€945/kW) of CAPEX levels which were around 1,350/kW in 2018 and are compensated by high capacity factors (at 22-25% in 2018) leading to LCOEs of €65/MWh. In the EU27 countries, soft costs are lower, leading to CAPEX levels of €940/kW in 2018, offset by lower capacity factors (from 9% to 20% in a few areas). China has the lowest CAPEX levels at €750/kW and a national average annual capacity factor recorded at 17%.

[4] Soft costs are the so-called national cost components of the CAPEX (costs in balance of plant, engineering, labour and others)

Figure 0-3 2018 LCOE results for EU27 vs. China, US, UK and other G20 - Wind & Solar



Number of observations per year

Technology	.EU27	.Other G20	China	United Kingdom	United States	Total
Solar PV - Utility-scale	31	17	1	4	8	**61**
Wind off-shore	10	1	1	4	1	**17**
Wind on-shore	37	20	1	3	7	**68**

Source: Authors' elaboration.

1 Mapping existing energy generation cost (LCOE) estimates (T2&T3)

This chapter identifies the generation costs of electricity and heat using different technologies. The report applies the methodology of levelised cost of electricity and heat (LCOE&LCOH). Although both LCOE and LCOH use the same methodology this report will use the term LCOE for power generating technologies and LCOH for heat generating technologies (all domestic systems). For combined heat and power (CHP) technologies, electricity and heat generation costs are calculated using an overall energy efficiency rate leading to overall energy output costs (see Annex A).

This methodology allows the comparison of different energy generation technologies over the period analysed (2008-2018). The analysis is made mostly at EU27 level, with a country specific approach available through the database provided with this report. The technologies covered are:

- Fossil fuel (FF)-Coal / Lignite: IGCC, Subcritical and Supercritical;
- FF-Natural gas: OCGT and CCGT;
- Nuclear;
- RES-Biogas;
- RES-Biomass (solid);
- RES-Geothermal;
- RES-Hydro: Hydro ≤ 10 MW and Hydro > 10 MW;
- RES-Solar: Solar PV - Utility-scale, Solar PV – Rooftop, Solar concentrated solar power (CSP);
- RES-Wind: Wind on-shore and Wind off-shore;
- Domestic heat pump;
- Domestic gas boiler (condensing);
- Domestic gas boiler (non-condensing);
- Domestic solar thermal;
- Domestic wood pellet boiler.

1.1 Summary of approach

Data collection has been ensured by for the construction of this report and the database consisted in developing a detailed template that was filled by national country experts. Years required for data provision were: 2008, 2010, 2013, 2016, and 2018 for renewable energy sources and domestic energy systems; and 2008, 2013, and 2018 for thermal energy sources, including nuclear. To complement the database, we used data from IRENA[5] and from Enerdata's Power Plant Tracker (PPT) database. Experts' submissions (composed of multiple sources and contributors such as energy agencies, governments, industry associations and industry agents[6]) contributed to 40% of the investment cost data in the database, IRENA contributed to another 40% and Enerdata's PPT to the remaining 20%. The database is composed of project specific data as well as national averages provided by different publications and contributors.

[5] The IRENA Renewable Cost Database is composed of project-specific cost data from multiple sources.
[6] Detailed sources are given in the database provided.

The collected data were used to calculate the LCOE using the formula below (the output of the formula represents power/heat generation cost per MWh):

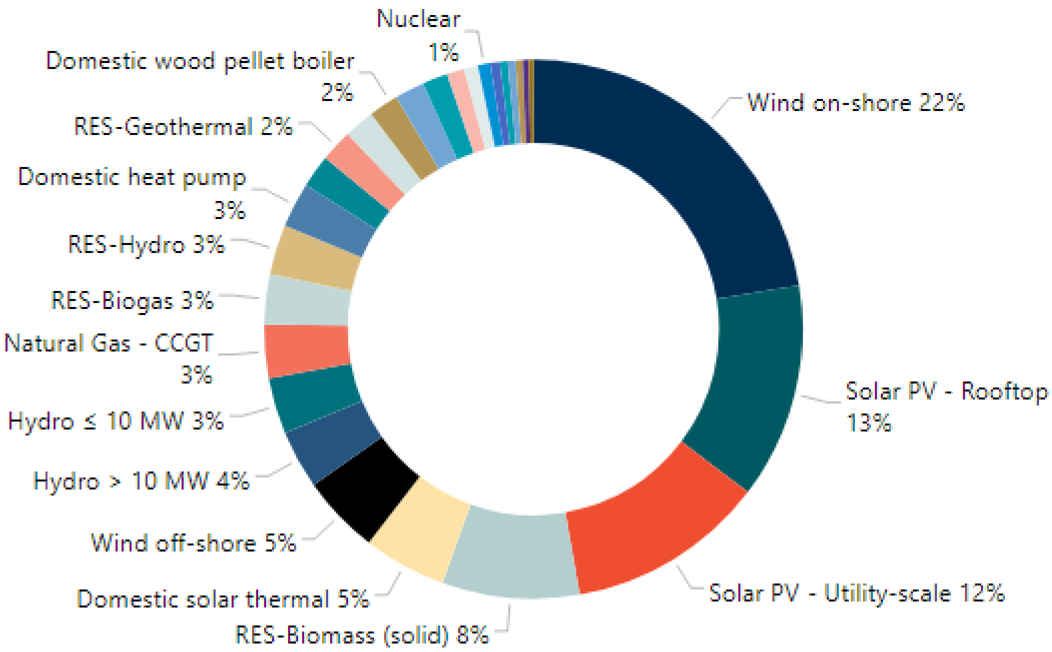
$$LCoE\&LCoH = \frac{Total\ lifetime\ cost}{Total\ lifetime\ energy\ prodution} = \frac{\sum_{t=1}^{n} \frac{I + FO\&M_t + VO\&M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

Where:

- I: Investment costs
- $FO\&M_t$: Fixed operation and maintenance costs in the year t
- $VO\&M_t$: Variable operation and maintenance costs excluding fuel costs in the year t
- F_t: Fuel costs in the year t
- E_t: Energy production in the year t
- r: Discount rate
- n: Expected asset lifetime

From the almost 2,000 observations[7] in the database, 22% is for wind onshore, 25% for solar PV and 8% for solid biomass. As expected, data for thermal technologies (coal and gas) is less abundant due to a low number of projects in the period analysed (most projects, especially in EU27 countries, are older than 2008). Most data for LCOE calculation were provided by the sources (expert submission, IRENA, and Enerdata), but in some cases, estimations were needed. The detailed estimations and methodology in those cases are described in Annex A.

Figure 1-1 Distribution of observation by technology



Source: Authors' elaboration.

[7] Each observation is the LCOE calculated using data provided by the sources (expert submission, IRENA and Enerdata's PPT). The sources provide a mix of project specific information and national averages. Details are provided in the database provided with this report.

1.2 Details regarding LCOE variables and methodology

The LCOE methodology allows for all costs engaged in the production of energy to be aggregated giving a result (or a range of results) that will serve as a proxy for the technology. Because the result is always in the same unit (in our case in €2018/MWh), the method allows for cross technology comparisons giving an estimation on which technologies are cheaper, despite their differences in dispatchability for example. This method is commonly used to establish price-based support instruments such as premiums, feed-in tariffs, contracts for difference and green certificates[8].
This methodology, however, has limitations. It does not take into consideration the revenue streams of the systems, level of competition, nor essential financial indicators for investment decisions. Furthermore, the comparison between technologies must be made with caution. The LCOE methodology does not include indicators based on the dispatchability and reliability of the technology. This means that it cannot reflect hourly market conditions which are strongly influenced by meteorological conditions (for intermittent renewables), fuel availability (for thermal systems), peak demand, and other factors. With all these aspects considered, the results presented in this report can be better understood and interpreted.

Across the database, overnight capital costs are used as data for the investment costs. Overnight capital costs already take into consideration costs related to the construction period of the power plants. O&M costs are divided into fixed and variable (FO&M and VO&M, respectively). FO&M typically includes insurance, labour costs, administration, fixed grid access fees and service contracts for scheduled maintenance. VO&M are all variable operating costs that are not fuel, related to unplanned maintenance, equipment replacement and incremental servicing and labour costs (IRENA, 2019).

In this report, LCOE results are presented using a discount rate of 3% for domestic systems and of 7% for all other technologies (renewables, nuclear and thermal). In the database provided with this report, results are also presented using discount rates between 2% and 4% for domestic systems and 6-8% for all other technologies.

All values (unless otherwise indicated) are in € of 2018. Other key variables such as plant lifetime are described in Annex A.

1.3 Main results

This section presents the main results of the LCOE database. Results are presented since 2008 for all technologies and the main graphs represent the LCOE ranges for the indicated years and technologies.

[8] (ECOFYS, 2014)

How to interpret the main result graphs

Box and whisker graphs showcase the minimum and maximum (whiskers) values of LCOE calculation for the indicated technology and years. The blue/green boxes represent second and third quartiles and orange dots represent the mean of each datasets. All percentage variations shown over time indicated in the text are based on the development of the simple (unweighted) means, as it was not possible to calculate weighted averages using the available data (installed capacity and number of projects were not available in most sources). Below each graph, a table indicates the amount of observations (LCOE results) that contribute to the graph.

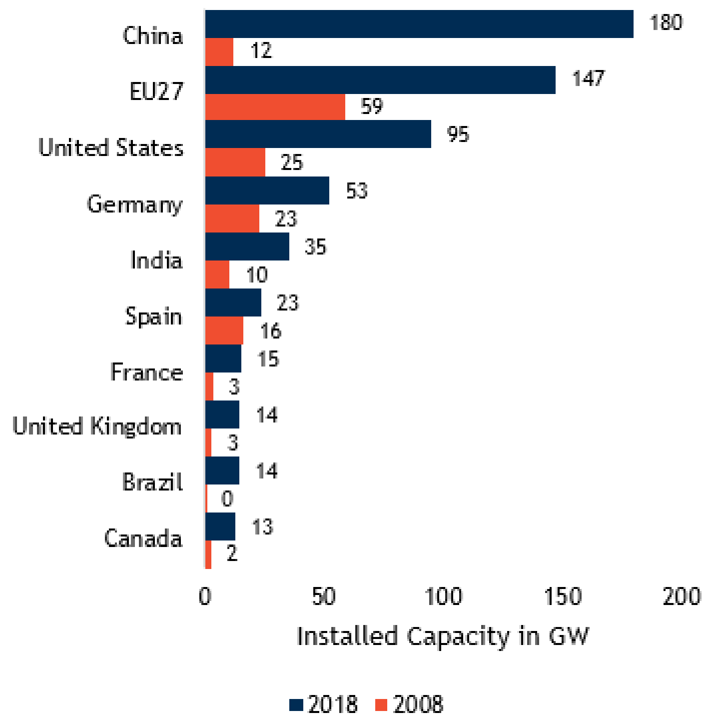
Beware to read the title of each section within the graph, as most compare G20 and EU27, but a few compare technologies within a country group (see e.g. hydropower and coal-fired).

The chapter begins with renewable technologies, in particular wind and solar, as those have the largest datasets and are the most dynamic markets in terms of capacity development in the period analysed. After renewables, thermal technologies and nuclear are presented followed by domestic systems.

1.3.1 Wind on-shore

Wind on-shore in the EU27 countries reached a total installed capacity of 162 GW in 2018. For this technology, the major markets internationally in terms of capacity are China (180 GW) and the US (95 GW). Within the EU27 countries, Germany has the largest installed on-shore wind capacity at 53 GW in 2018.

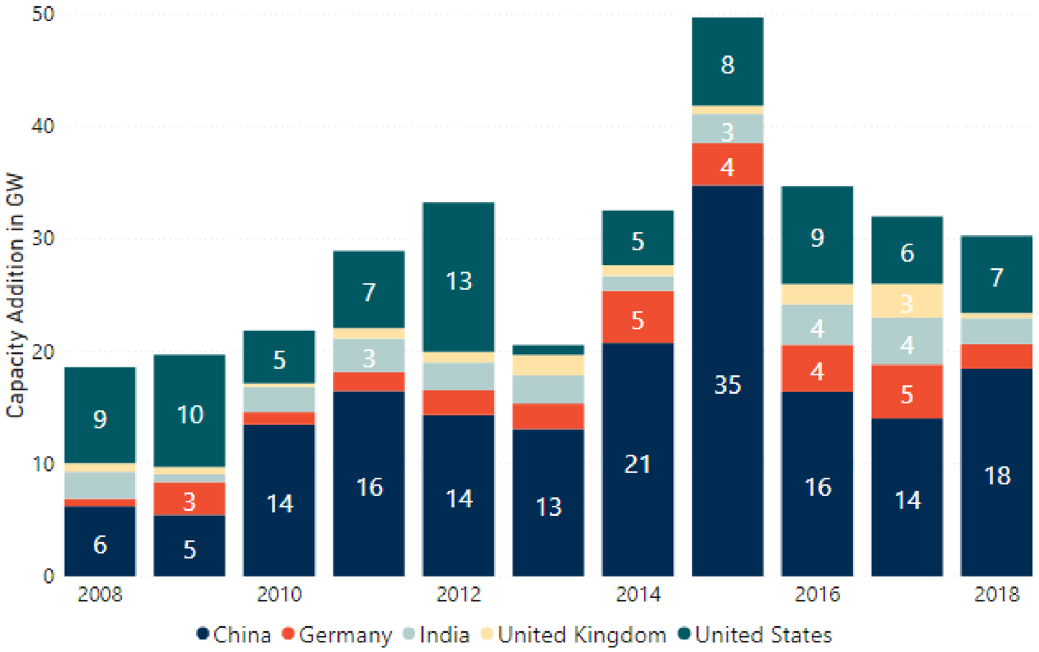
Figure 1-2 Installed Capacity in 2018 - Wind on-shore (GW)



Source: Enerdata GED database.

The largest market in terms of net capacity addition is China that has added 174 GW from 2008 to 2018[9], followed by the US with almost 80 GW added to the grid from 2008 until 2018. The total added capacity in the EU27 was 108 GW, and almost 330 GW in the non-EU G20 group (from 2008 to 2018).

Figure 1-3 Main markets in terms of annual capacity additions - Wind on-shore (GW)



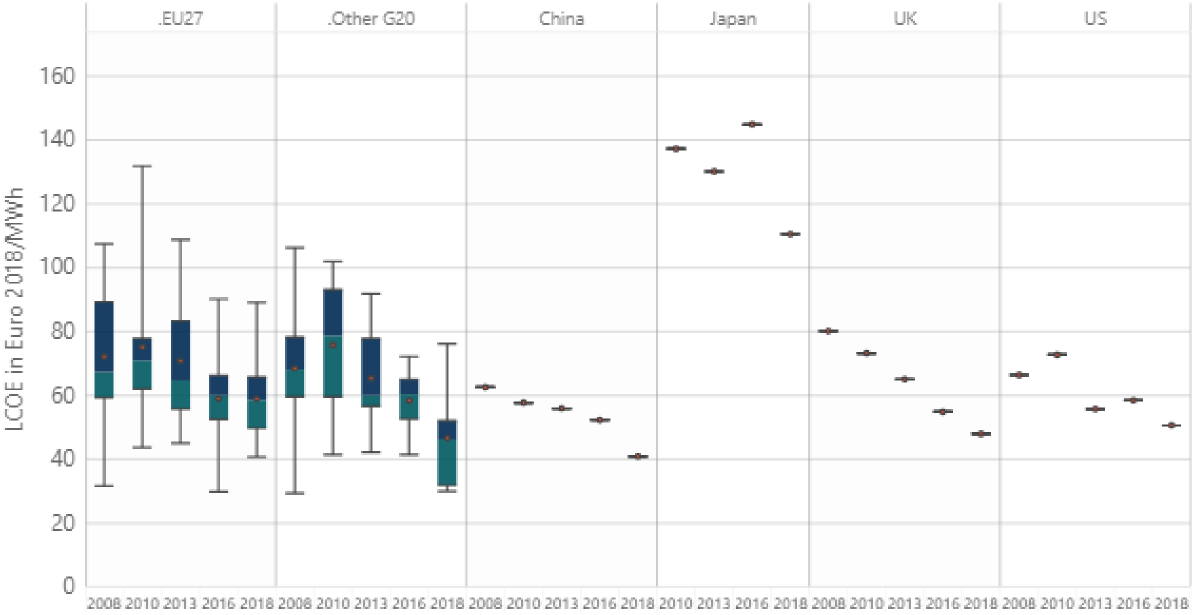
Source: Enerdata GED database.

LCOE for wind onshore in the EU27 countries (mean values) have dropped 21% since a temporary increase in 2010, until 2018, and 18% since 2008. In 2018, LCOE ranged between €41-89/MWh with 75% of results being below €66/MWh. While projects are always site and market specific, a very slight increase in overall costs is registered between 2016 and 2018 most likely due to increase in country specific costs (balance of plant, labour costs, connection to the grid, etc.) within the initial investments. Furthermore, the overall cost drop prior to 2008, and to some extent also in the analysed period, is clearly driven by capacity factor improvements explained by one-third by technological improvements[10] (IRENA, 2019). Average annual capacity factors in the EU27 countries went from 27% to 32% between 2008 and 2018.

LCOE for wind on-shore in the other G20 countries outside EU27 have dropped 35% by 2018 since their peak in 2010. LCOE in those countries in 2018 ranged between €30-110/MWh with 75% of results being below €57/MWh. Average capacity factors in the G20 non-EU27 countries went up from 32% to 36% between 2008 and 2018.

[9] 2018 added installed capacity is calculated deducting 2017 from 2018 total IC.
[10] Larger turbines, along with higher hub heights and larger rotor diameters.

Figure 1-4 LCOE results for EU27 and G20 - Wind on-shore



Number of observations per year

Country group	2008	2010	2013	2016	2018	Total
EU27	26	61	71	66	37	**261**
G20	21	25	40	37	32	**155**

Orange dot is the dataset's mean, lower whisker is the minimum while higher whisker is the maximum value observed. Boxes represent second and third quartiles.

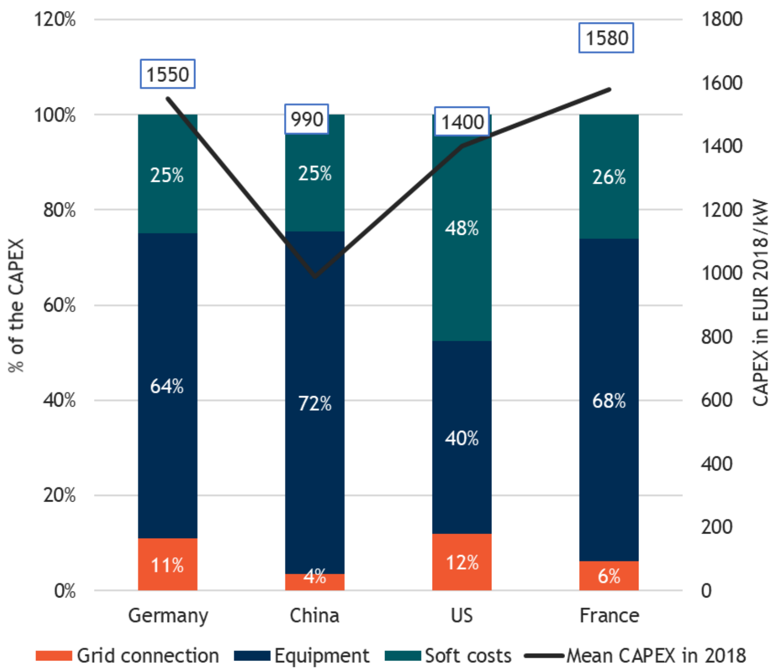
Source: Authors' elaboration

CAPEX levels between the US and the EU27 are somewhat similar (in 2018 at €1,400/kW and €1,600/kW, respectively). Power plants in these regions, however, face very different operational realities. Capacity factors in the US are higher than those registered in newly installed projects in Europe. In 2018, the average capacity factor in the US was 36% while in Europe it was around 32%. Furthermore, differences in OPEX levels are also significant, with such costs in the US at €40/kW/year being much higher than in Europe at €30/kW/year. The Chinese market presents rather low LCOE for wind. CAPEX for the technology were around €1,000/kW in 2018, while capacity factors were at around 30% and OPEX levels around €24/kW/a.

Taking all these variables into account, LCOE in China is the lowest at €40/MWh in 2018, followed by the US at €50/MWh and Europe at €60/MWh on average.

As CAPEX levels are one of the main determinants for LCOE, the graph below showcases the breakdown of CAPEX in certain countries. Germany and France, with very similar CAPEX levels and structures, showcase that grid connection and soft costs represent over 30% of the CAPEX. In the US, those costs are much higher (60% of CAPEX levels). China has lower soft costs and grid connection costs leading to lower CAPEX levels.

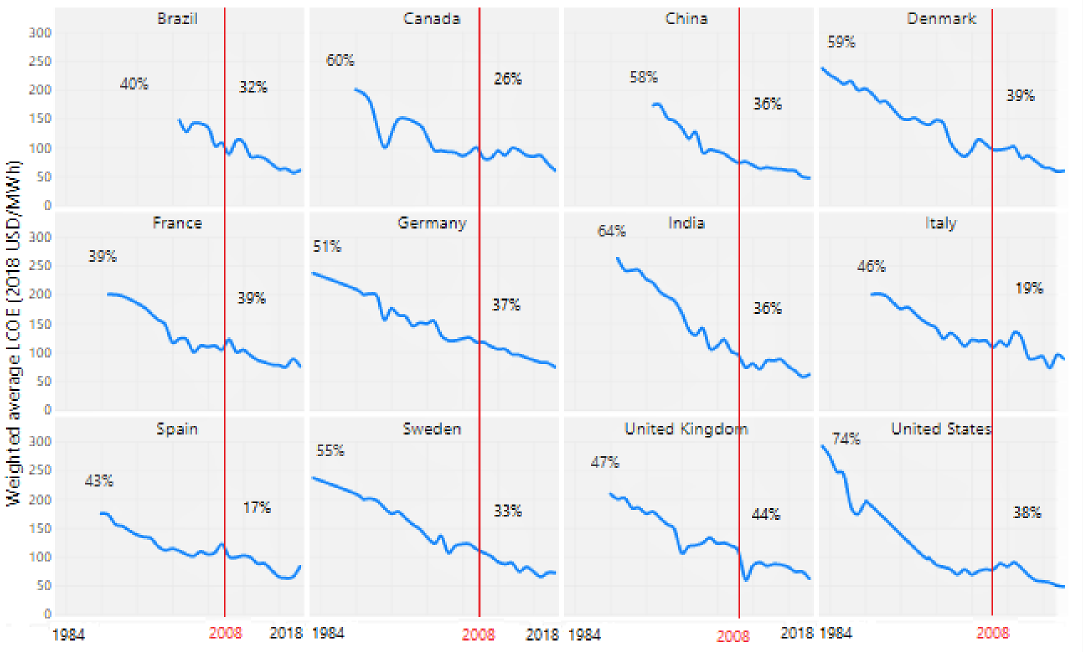
Figure 1-5 Capex breakdown for wind onshore in China, US, France and Germany (%)



Source: Cost breadown from Agora Future Cost of Wind (2017, p21) for Germany; IRENA (2019, figure 5.6) for China; NREL Cost of Renewable Energy Spreadsheet Tool (CREST), Wind version 1.4 for the US and ADEME 2017 Étude sur la filière eolienne française, page 297 for France. Mean CAPEX values in 2018 from the database.

As a major drop in costs for this technology already started before 2008 (see figure below), more recent decreases seem to be driven by mild changes in turbine costs and balance of project costs, and pronounced increases in capacity factors (led by metereological conditions, technology advancements and higher towers).

Figure 1-6 The weighted average LCOE of commissioned wind on-shore projects (1984-2018)

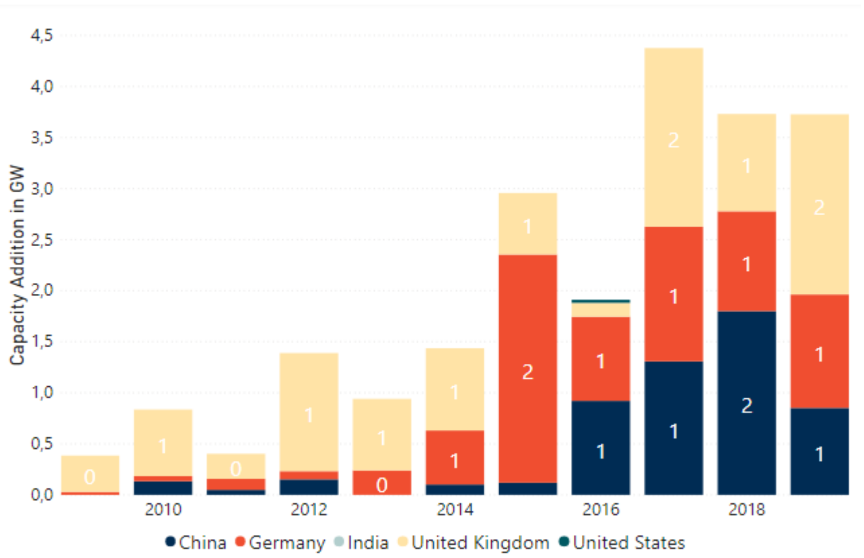


Source: based on LCOE results of IRENA (2019), to the left of the red line the rate of decline prior to 2008, to the right from 2008 until 2018[11].

1.3.2 Wind off-shore

The UK is the largest market in terms of installed capacity of off-shore wind (8 GW in 2018), followed by Germany (6.4 GW), China (4.6 GW), and Denmark (1.7 GW). European countries are responsible for almost 80% of net capacity additions in the period (17 GW of a total of 22 GW added between 2008 and 2018). Germany and the UK are responsible for the largest increases in capacity among the studied countries (6.4 GW and 7.5 GW respectively) between 2008 and 2018.

Figure 1-7 Main markets in terms of capacity additions - Wind off-shore (GW)



Source: Enerdata GED database.

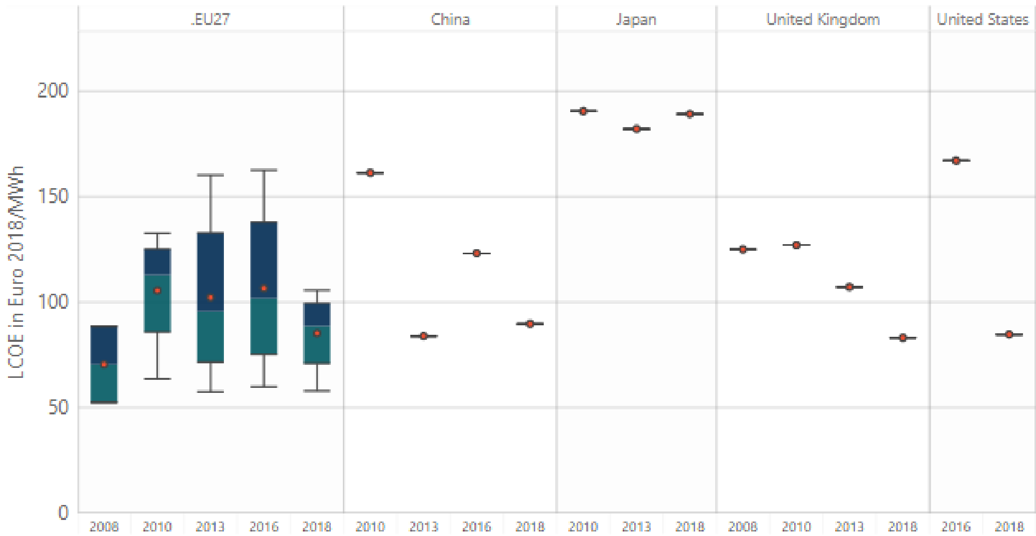
[11] As expected due to similarities in data sources and estimates, the study's LCOE estimates are in line with those from IRENA (2019).

LCOEs in the EU27 have remained somewhat stable between 2008 and 2018, with a more significant drop between 2016 and 2018 (-20%). In 2018, costs ranged between €57-106/MWh (mostly below €100/MWh). Costs are very project-specific and vary significantly depending on the location, distance from shore, depth of installations, etc. More recent projects use larger turbines, expanding capacity, reducing installation costs and allowing for higher capacity factors. This has, however, been offset somewhat by the fact that power plants have been installed in deeper waters and further away from the shore leading to increases in installation costs. For the LCOE calculations in this report, CAPEX include turbine costs, turbine installation, foundation, electrical infrastructure (including substation and grid connections costs borne by the project developer).

The average capacity factors have increased from 40% in 2008 to 45% in 2018. The highest LCOE are seen in Germany (€90/MWh in 2018) and Belgium (€93/MWh). In the UK, LCOE average levels for off-shore wind were at €83/MWh and registered a 34% drop in costs since 2008.

In the non-EU G20 countries, data availability is quite low (only 19 observations were collected). LCOE for off-shore wind have dropped significantly from around €175/MWh in 2010 to €105/MWh in 2018. In 2018, costs ranged between €60-190/MWh and remained mostly below €140/MWh. For this year, 4 LCOE were calculated: for the US (€85/MWh), Japan (€190/MWh), China (€90/MWh), and Canada (€62/MWh).

Figure 1-8 LCOE results for EU27 and G20 - Wind off-shore



Number of observations per year

Country group	2008	2010	2013	2016	2018	**Total**
EU27	4	10	12	9	10	**45**
G20	2	7	16	8	8	**41**

Source: Authors' elaboration.

With relatively low capacity additions being registered for this technology, and due to projects' specificities (location, distance from shore, depth of installations, etc.), LCOE results are rather volatile over time in all countries. As developers are moving further offshore and into deeper waters adding to installation and development costs, with this, gains in the large-scale production of turbines are offset. Differences between countries are thus due to project-specific aspects rather than stronger effect in capacity factors and OPEX levels.

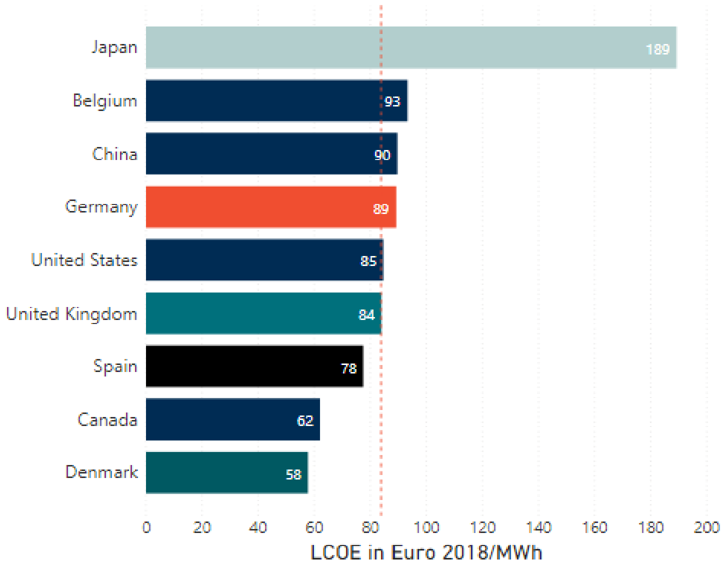
An important aspect to be considered when analysing LCOE results from different countries is the issue of grid connection costs. In Denmark, the Netherlands, Germany, and China, for instance, grid connection assets are built and owned by either a Transmission System Operator (TSO) or other public bodies (IRENA, 2020), i.e. transmission costs are socialised (IEA, 2018). This means that the project's specific CAPEX are lower and transmission assets are considered separately. In Germany, the offshore grid connections are developed, owned, and operated by the TSOs. The country had the so-called "reactive TSO model" until 2013, which meant TSOs were obliged to guarantee grid connection to any project upon the developers' request. After 2013 under the Offshore Grid Development Plan (O-NEP), the "proactive TSO model" was established. Instead of responding to any developer's request for grid connection TSOs would establish an allocation procedure that allows for transmission assets to be shared across individual wind farms (Schittekatte, 2017). In the Netherlands, transmission costs are also borne by TSOs and the Dutch consenting regime (IEA, 2018). In the UK, since 2009, specific tenders for the transmission assets are organised to allow Offshore Transmission Owners (OFTOs), to compete for their ownership and operation. Before 2009, all grid connection costs were borne by the project's developer.

In Belgium, the US and Japan, transmission costs are the responsibility of the power plant's developer. In Belgium, however, costs are partially subsidised with the costs of the subsidy borne by the TSO (up to 33% of CAPEX to a maximum of €25m). In the US, the transmission assets are built and operated by the developer, while in Japan the transmission lines are owned by the electricity company and the developer is expected to pay for connecting the facility to the grid (IEA, 2018).

China presents the lowest CAPEX levels, around €2,200/kW, but they are offset by relatively low capacity factors (around 30% in 2018). Meanwhile, the US and the European countries present more similar CAPEX levels at €3,000/kW and €3,300/kW, respectively, and capacity factors between 45-50%.

Japan has some of the highest CAPEX levels in 2018 at €4,100/kW. The country's commercial offshore wind development is in its initial phases with most capacities being demonstration projects. Furthermore, as already mentioned, transmission costs are the responsibility of the developer. This only partially explains the high LCOE levels, with a lower average wind speed (8.7 metres/second), and consequently low capacity factors (28%), explaining the rest.

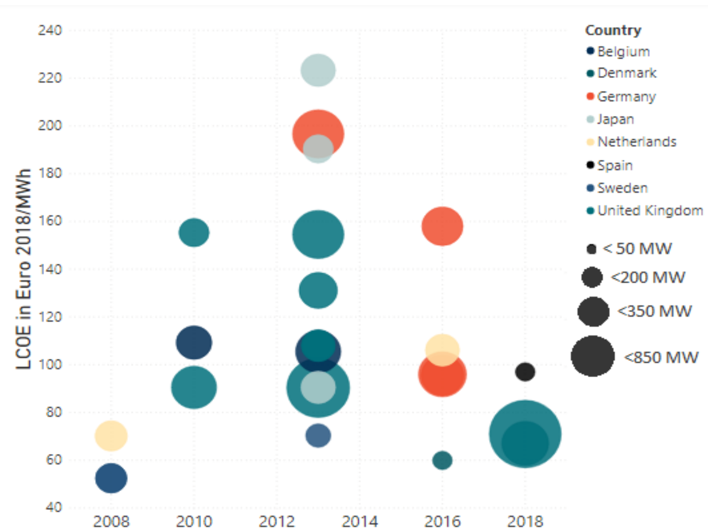
Figure 1-9 LCOE results Wind Off-shore 2018



Orange Line is the EU27 mean LCOE for the technology (2018)

Source: Authors' elaboration.

Figure 1-10 LCOE results for Wind off-shore projects by Installed Capacity

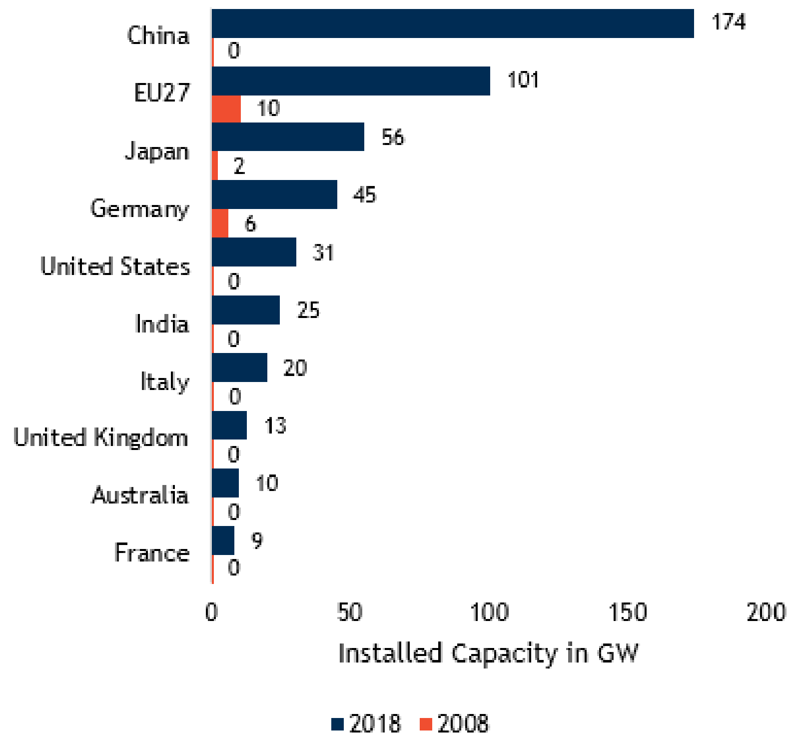


Source: Authors' elaboration.

1.3.3 Solar PV

China's Solar PV installed capacity (including rooftop and utility-scale) has reached 174 GW in 2018. The second largest market in terms of total installed capacity is Japan (56 GW) followed by Germany (45 GW) and the US (31 GW).

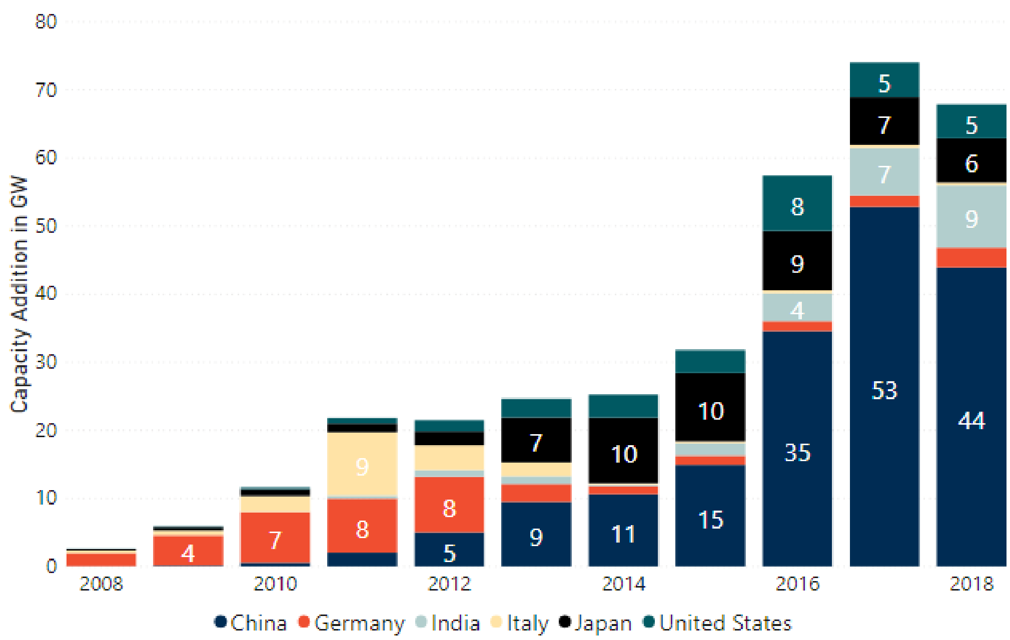
Figure 1-11 Installed Capacity in 2018 - Solar PV (GW)



Source: Enerdata GED database.

China has driven the world expansion in recent years. Since 2008, the country's net capacity addition reached 174 GW of solar PV. In the EU27 108 GW of solar PV capacity were added since 2008 while 316 GW were added in the non-EU G20 countries (net capacity additions). Japan was the second largest market in terms of capacity addition (+53 GW), followed by Germany (almost 41 GW), the US (over 30 GW), India (25 GW), and Italy (20 GW).

Figure 1-12 Main markets in terms of annual capacity additions - Solar PV (GW)



Source: Enerdata GED database.

Solar PV - Rooftop

In this report, solar rooftop is considered all PV power systems installed at roof tops in the residential and commercial sectors. Systems are all under 1 MW of installed capacity as per the classification of the IEA Photovoltaic Power Systems Program (IEA PVPS)[12].

Power generation costs for Solar PV - Rooftop in the EU27 countries have dropped almost 80% since 2008. In 2018, LCOE of rooftop solar PV ranged between €70-188/MWh, with 75% of results being below €153/MWh. In the UK costs droped by almost 60% in the period reaching €173/MWh in 2018. In this country, high costs are explained by the low capacifty factors at 10% (3 p.p. below the EU27 average).

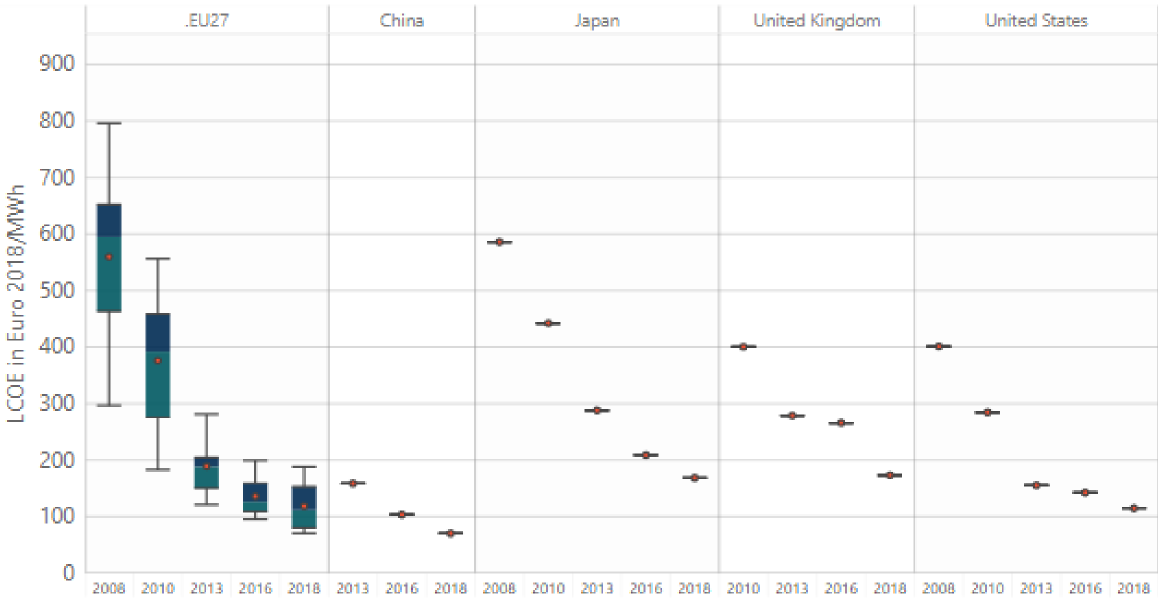
The reduction in LCOE was driven by drastic drops in CAPEX levels. For instance, between 2013 and 2018, solar PV module prices declined between 34% and 61% depending on the market (country) (IRENA, 2019).

Costs in the other G20 countries outside EU27 have dropped in similar proportion (around 75%) since 2008. In 2018, LCOE in those countries ranged between €42-168/MWh, with 75% of results being below €101/MWh. The lowest LCOE levels in 2018 are seen in Turkey and India, both countries combining high solar irradiation rates (capacity factors at 21% and 18%, respectively) and low CAPEX levels (at €680/kW and €800/kW respectively) as costs related to installation and balance of plant are much lower than those seen in the EU27 and other developed G20 countries.

Cost distribution in non-European countries varies, with LCOE in Canada, the US, and Japan much higher (above €100/MWh in 2018) than those observed in other countries. This is due to higher soft costs within the investment costs, i.e. costs in balance of plant, engeneering, labour and other national cost components.

[12] Reference national reports published in: https://iea-pvps.org/national-survey-reports/

Figure 1-13 LCOE results for EU27 and G20 - Solar PV - Rooftop



Number of observations per year

Country group	2008	2010	2013	2016	2018	**Total**
EU27	15	11	30	22	55	**133**
G20	11	15	21	18	45	**110**

Source: Authors' elaboration.

Solar PV - Utility-scale

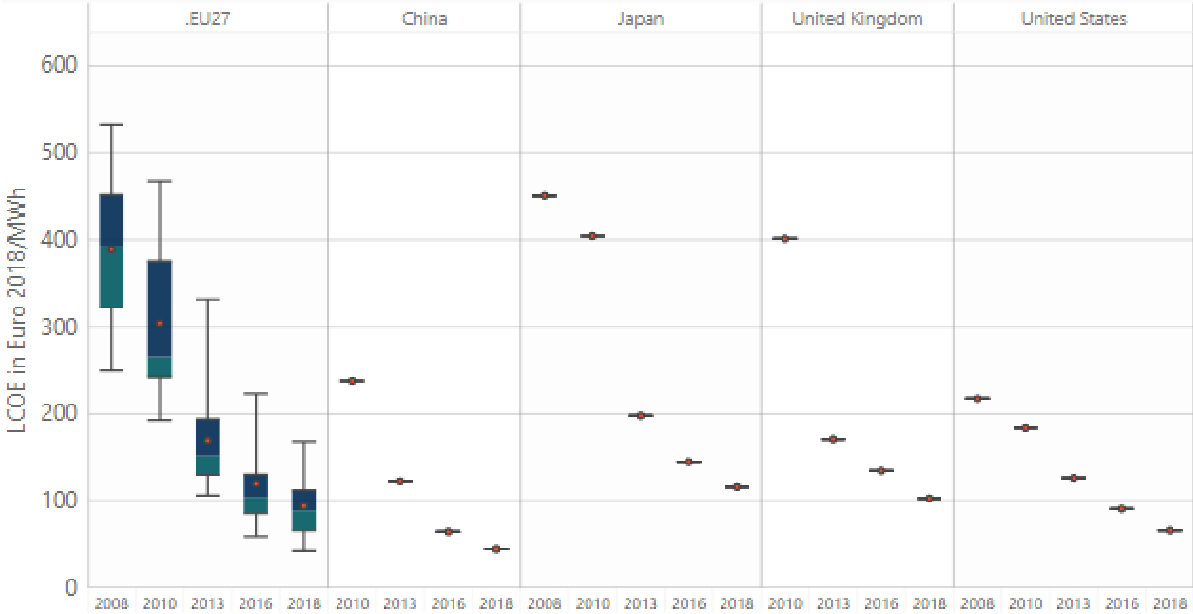
Utility-scale PV systems are all ground-mounted power plants with installed capapcity above 1 MW as per the classification of the IEA Photovoltaic Power Systems Program (IEA PVPS)[13].

Power generation costs for Solar PV Utility-scale in the EU27 countries (mean values) have dropped by 75% since 2008. In 2018, LCOE ranged between €43-168/MWh with 75% of results being below €112/MWh. According to IRENA, the technology has the highest learning rates and recent power purchase agreements (PPA) and tender prices in certain markets indicate that prices could drop below US$48/MWh (around €43/MWh). In the UK LCOE in 2018 was around €103/MWh and the country registered a drop in costs of 74%.

LCOE in other non-EU G20 countries have dropped by 80% since 2008. In 2018, LCOE in those countries ranged between €32-145/MWh with 75% of results being below €71/MWh. Differences in LCOE levels in EU27 countries and non-EU G20 countries are explained by the level of national cost components of CAPEX (balance of plant, engeneering, labour and others), which are higher in Europe. The only countries with higher LCOE levels (above €100/MWh in 2018) are Canada and Japan. In those coutries, as well as in the US, soft costs (non-equipment related) are much higher than in other G20 countries.

[13] Reference national reports published in: https://iea-pvps.org/national-survey-reports/

Figure 1-14 LCOE results for EU27 and G20 – Solar PV Utility-scale



Number of observations per year

Country group	2008	2010	2013	2016	2018	**Total**
EU27	26	18	31	21	31	**127**
G20	7	17	21	22	31	**98**

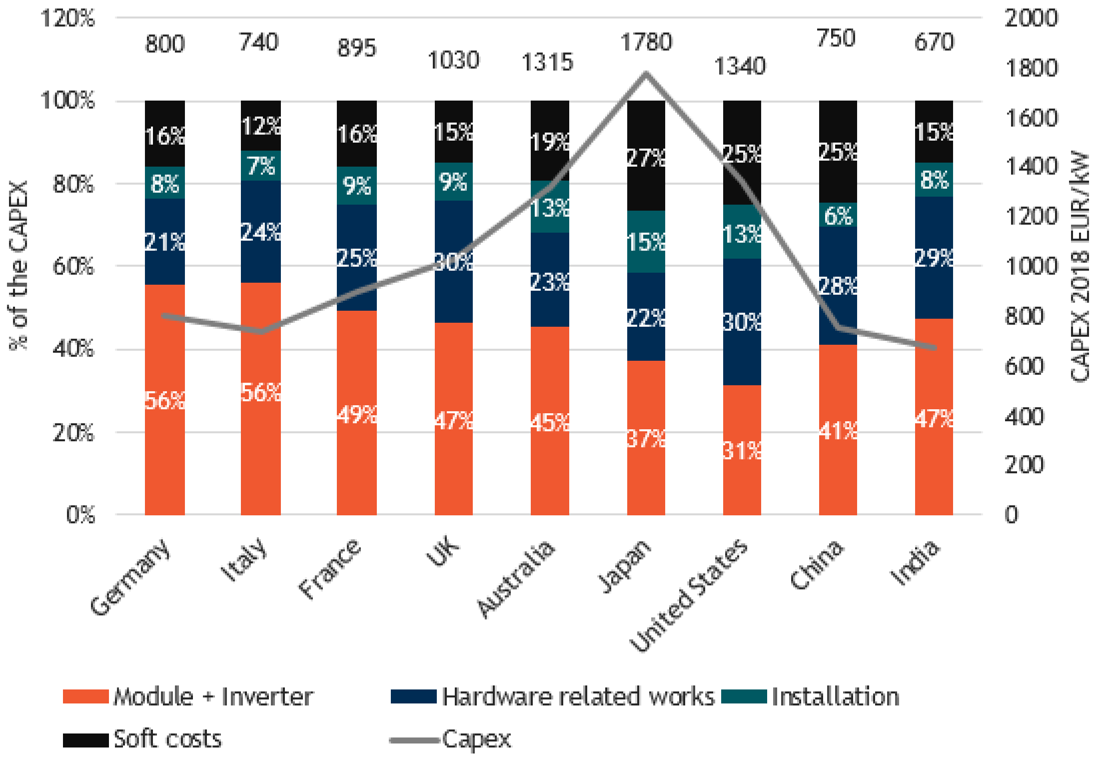
Source: Authors' elaboration.

The differences in LCOE results are mainly explained by two aspects: capacity factors (based on the country's solar irradiation) and the level of "soft costs"[14] and installation within the CAPEX (IRENA 2019). Despite a convergence of the costs of modules, inverters and overall equipment in the international markets, national costs are very different from country to country. In Japan for instance, of the median €1,780/kW CAPEX (2018), over 60% are soft and installation costs. In the US, those costs correspond to over 70% of CAPEX levels which were around €1,340/kW in 2018. In the US, these costs are offset by very high capacity factors (at 25% in 2018), which is not the case in Japan (16% in 2018). In these countries, LCOE was around €65/MWh (US) and €115/MWh (Japan).

In the EU27 countries, soft costs are not as high leading to CAPEX levels of €900/kW in 2018, compensating for the low capacity factors (around 15%). It is important to keep in mind that capacity factors in the EU27 vary from country-to-country: higher capacity factors (between 17% and 20%) are seen in countries like Greece and Portugal, medium rage capacity factors (12-16%) are registered in countries such as Germany and France, and lower capacity factors (below 12%) are seen in northern countries such as Poland and the Netherlands. China has the lowest CAPEX levels at €750/kW and capacity factors around 17% resulting in LCOE of €45/MWh.

[14] Soft costs are the so-called national cost components of the CAPEX (costs in balance of plant, engineering, labour and others)

Figure 1-15 Capex breakdown for solar in selected countries (%)



Source: *IRENA (2019, based on figure 3.7)[15], CAPEX levels from database.*

1.3.4 Concentrated solar power (CSP)

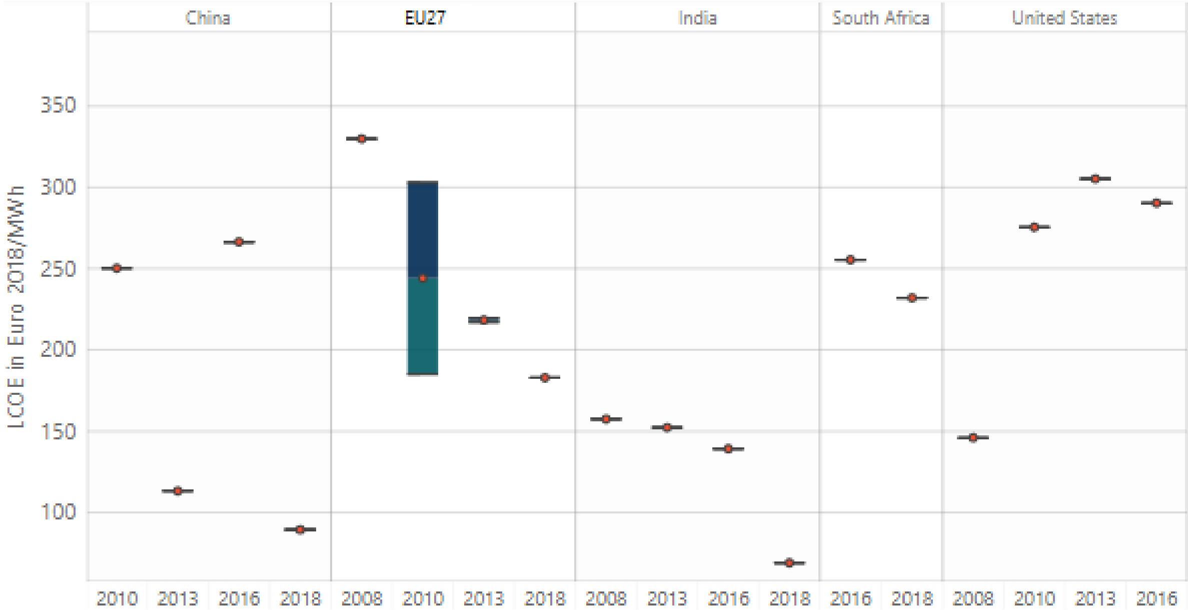
In terms of total installed capacity, Spain and the US are the top two countries with 2 GW each. Net capacity additions occured mostly around 2013.

Power generation costs for Solar CSP in the EU27 countries (mean values) have dropped 44% since 2008. In 2018, LCOE were around €183/MWh. For this technology, only 15 observations (LCOE calculations) were available for EU27 countries (France, Greece and Spain).

LCOE in the other G20 countries outside EU27 were calculated using 19 observations (US, China, South Africa and India). Despite the impossibility of deriving a clear trend with such few observations, an overall reduction in costs of 15% is observed in the period. In 2018, LCOE in those countries ranged between €69-234/MWh, with 75% of results being below €160/MWh. India and China have the lowest LCOE levels due to very low CAPEX (€3,600/kW and €1,500/kW respectively) compared to levels observed in South Africa and the US (in 2016) (€8,900/kW and €8,440/kW, respectively).

[15] Hardware related works: cabling / wiring, grid connection, monitoring and control, racking and mounting, safety and security. Installation: electrical installation, inspection, mechanical installation. Soft Costs: customer acquisition, financing costs, incentive application, margin, permitting, system design (IRENA, 2019).

Figure 1-16 LCOE results for EU27 and G20 - Solar CSP



Number of observations per year

Country group	2008	2010	2013	2016	2018	**Total**
EU27	2	8	4		1	**15**
G20	2	4	6	4	3	**19**

Source: Authors' elaboration.

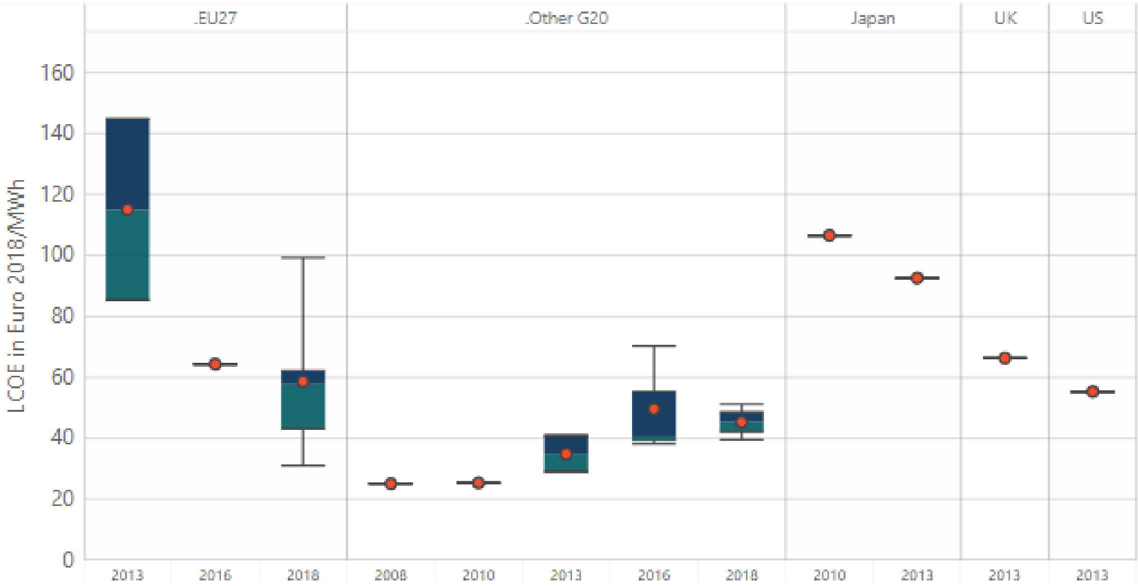
1.3.5 Geothermal

The US and Indonesia have the largest geothermal power plant fleets (4 GW and 1.9 GW, respectively). In the recent years, Turkey added 1.25 GW, Indonesia added 890 MW and the US added 540 MW. Italy is the only EU27 country with significant net capacity additions between 2008 and 2018 (+100 MW).

Power generation costs for Geothermal in the EU27 countries (mean values) have dropped 50% since 2013, for the 13 observations collected. In 2018, costs ranged between €30-100/MWh.

LCOE in the non-EU G20 countries outside EU27 were calculated using 22 observations. The overall reduction of 30% is observed from 2010 until 2018. In 2018, LCOE in those countries ranged between €40-50/MWh.

Figure 1-17 LCOE results for EU27 and G20 - Geothermal



Number of observations per year

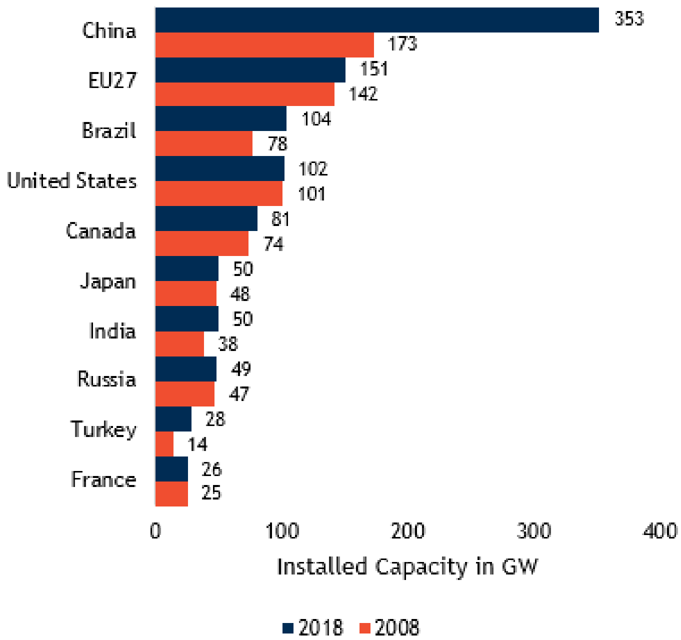
Country group	2008	2010	2013	2016	2018	**Total**
EU27			3	1	9	**13**
G20	1	3	9	4	7	**24**

Source: Authors' elaboration.

1.3.6 Hydropower

In terms of total installed capacity, China is the largest hydropower market with 353 GW in 2018, followed by Brazil (104 GW) and the US (102 GW). Between 2008 and 2018,in terms of net capacity addition, China added 207 GW of hydropower capacity, Brazil added 27 GW, Turkey 15 GW and India 13.5 GW.

Figure 1-18 Installed Capacity in 2018 - Hydropower



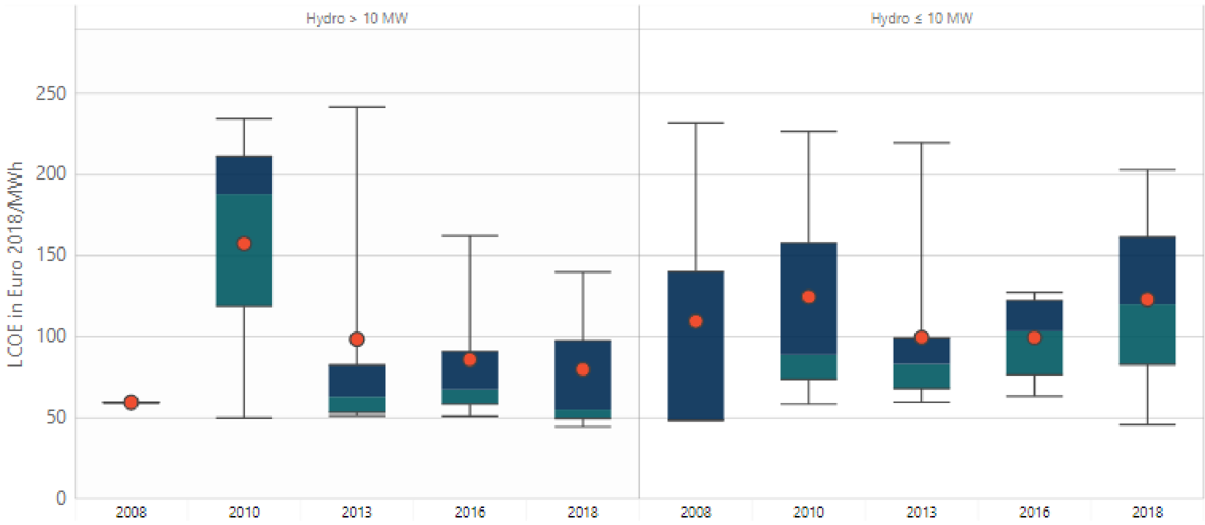
Source: Enerdata GED database.

Power generation costs for hydropower are divided into projects over 10 MW (larger scale) and under 10 MW (small-scale). Costs for hydropower plants are very site-specific and projects (in particular in the EU27) are very scarce. This leads to a small sample of results with high variation. In this database, multiple technologies are considered (run-of-river and dam) also explaining the large ranges in LCOE results.

From 2008 to 2018, in the EU27 countries, large-scale projects presented costs from €60/MWh to €80/MWh. Despite registering LCOE levels rather low in 2008 and high in 2010, the overall trend is fairly constant. In 2018, LCOE ranged between €44-140/MWh with 75% of the values being under €100/MWh. Small-scale projects in the period presented costs from €110/MWh in 2008 to €123/MWh in 2018. In 2018, costs ranged between €46-203/MWh, with 75% of the values being under €160/MWh.

Very few observations were registered for the UK which had an LCOE of €85/MWh in 2018 for large-scale hydropower and €116/MWh for small-scale hydropower.

Figure 1-19 LCOE results for EU27 - Hydropower > 10 MW and Hydropower ≤ 10 MW



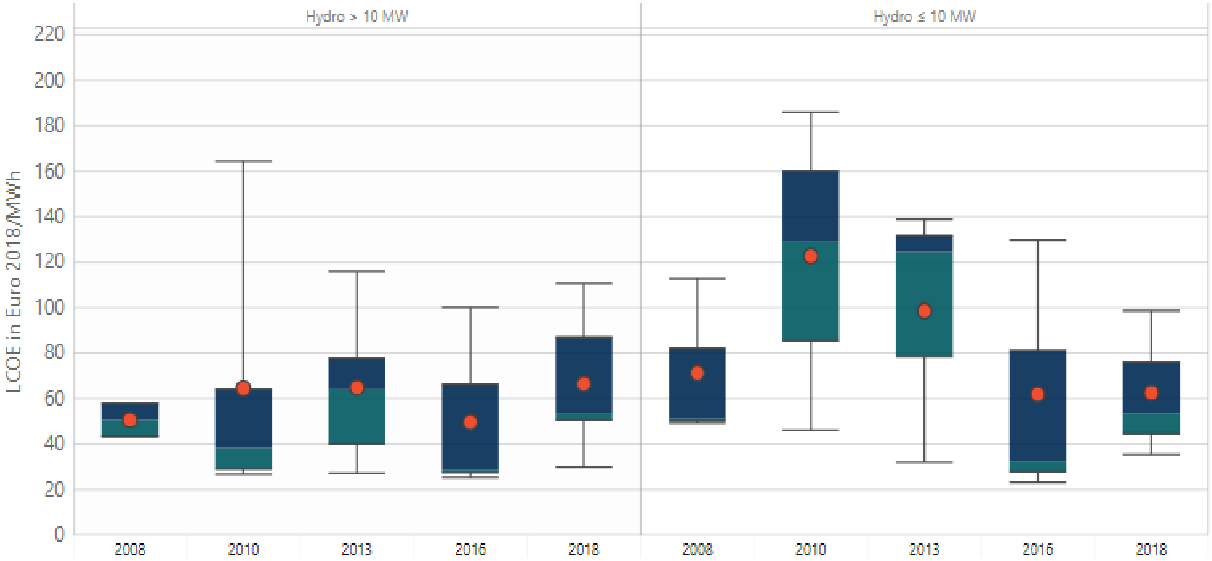
Number of observations per year

Technology	2008	2010	2013	2016	2018	Total
Hydro > 10 MW	1	3	11	11	5	31
Hydro ≤ 10 MW	4	5	10	6	7	32

Source: Authors' elaboration.

Costs in the other G20 countries for large-scale hydropower increased by 30% from €50/MWh to €66/MWh. In 2018, large-scale hydropower LCOE costs ranged between €30-110/MWh, with 75% of the values under €87/MWh. Small-scale projects costs in the period decreased from €71/MWh in 2008 to €62/MWh in 2018 (-13% in the period, -50% between 2010 and 2018). In 2018, costs ranged between €36 and 100/MWh, with 75% of the values being under €76/MWh.

Figure 1-20 LCOE results for G20 - Hydropower > 10 MW and Hydropower ≤ 10 MW



Number of observations per year

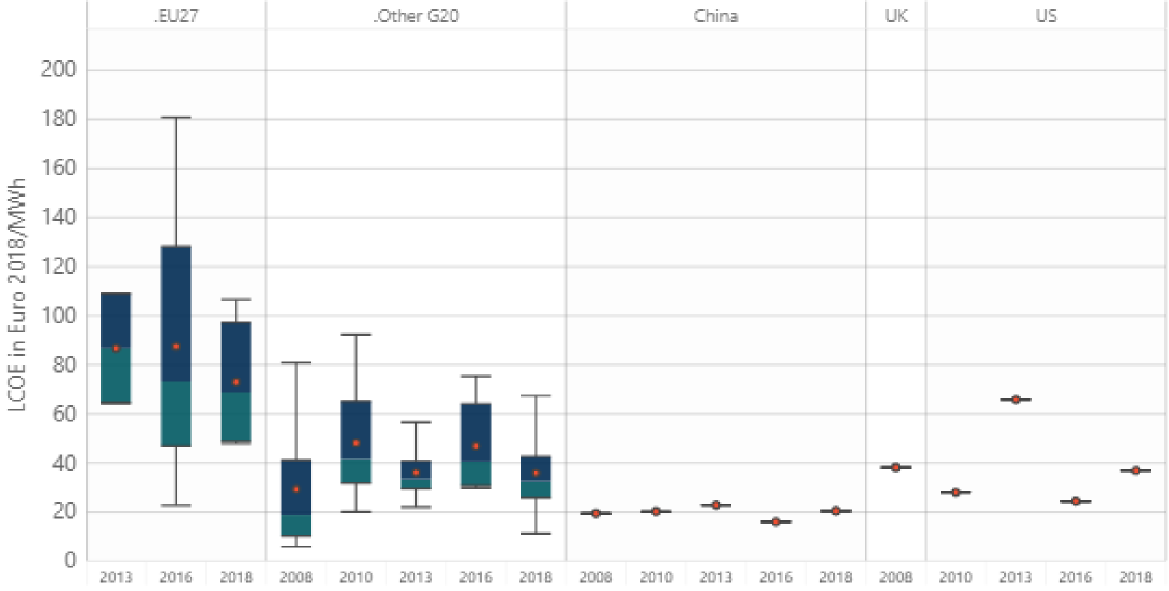
Technology	2008	2010	2013	2016	2018	Total
Hydro > 10 MW	3	6	6	6	9	30
Hydro ≤ 10 MW	4	6	5	6	5	26

Source: Authors' elaboration.

In comparison, LCOE calculated with inputs provided by IRENA for all hydropower projects (without project size breakdown) show that LCOE in the EU27 countries dropped since 2013 from €87/MWh to €73/MWh in 2018. In 2018, average LCOE ranged between €47-106/MWh.

For the non-EU G20 countries, the LCOE increased by 20% in the period, with results in 2018 ranging between €11/MWh and 67/MWh (75% of values are under €40/MWh). The significant variation of costs seen in the EU27 countries is not registered in G20 countries. This is simply due to the fact that projects in the EU27 are much rarer (and most likely of a much smaller scale) and the main hydropower potential has been exploited prior to 2008. The lowest LCOE are seen on China, as a result of largescale development. In 2018 the country's mean CAPEX was around €1,000/kW resulting in LCOE of around €20/MWh.

Figure 1-21 LCOE results for EU27 and G20 - Hydropower (inputs from IRENA)



Number of observations per year

Country group	2008	2010	2013	2016	2018	**Total**
EU27			2	4	4	**10**
G20	8	12	10	8	7	**45**

Source: Authors' elaboration.

1.3.7 *Biomass (solid)*

The countries with the largest installed capacity for biomass are the US (16 GW), Brazil (15 GW) and Germany (11 GW). In terms of net capacity addition, 60 GW of biomass and waste-fired capacity was added between 2008 and 2018, 35 GW in the G20 countries (Brazil +11 GW, India +8 GW, and China +6.5 GW) and 25 GW in the EU27 countries (Germany +6.2 GW, and Italy +5.3 GW) and+5.8 GW in the UK.

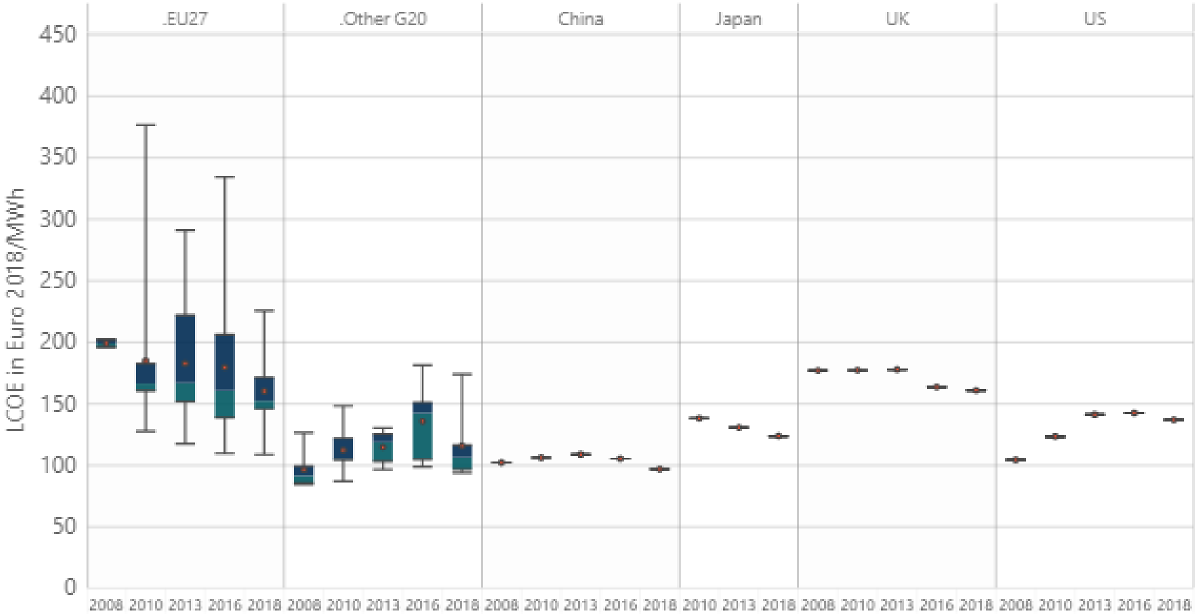
LCOE of solid biomass-fired power plants have dropped by 20% since 2008 to €160/MWh on average (in 2018 LCOE ranged between €108-€225/MWh). In the UK costs dropped 10% reaching €160/MWh in 2018. The trend is driven by recent reductions in wood costs which started in 2014[16] and more importantly a reduction in CAPEX levels which were on everage at €4,100/kW in 2008 and €2,700/kW in 2018.

With fuel costs around 30% lower than for EU27 countries and the UK, LCOE in non-EU G20 countries were between €94-174/MWh in 2018. Over the period, LCOE rates remained rather stable in most countries. Unlike other technologies, Japan's LCOE are lower than in the US; this is due to a higher capacity factor, i.e. higher utilization rates of biomass-fired power plants in Japan.

In China biomass has LCOE of €96/MWh, in Japan €124/MWh and in the US €137/MWh (in 2018). The lowest CAPEX levels are seen in China €1,000/kW, while in the US they range from €2,000 to 3,500/kW and Japan's CAPEX are around €3,100/kW.

[16] EU average estimates based on expert submission and IEA's Global Wood Pellet Industry and Trade Study 2017 (http://task40.ieabioenergy.com/wp-content/uploads/2013/09/IEA-Wood-Pellet-Study_final-2017-06.pdf). Conversion of wood costs considers the heat content of dry wood to be around 18.5-21 MJ/kg one ton of biomass (wood) produces around 5.5 MWh in a system with 100% efficiency. The chosen fuel costs for the EU 27 and the UK can lead to an overestimation as wood pellets are more expensive than other wood products used for power generation.

Figure 1-22 LCOE results for EU27 and G20 – Biomass (solid)



Number of observations per year

Country group	2008	2010	2013	2016	2018	**Total**
EU27	3	17	19	23	8	70
G20	13	22	22	12	17	86

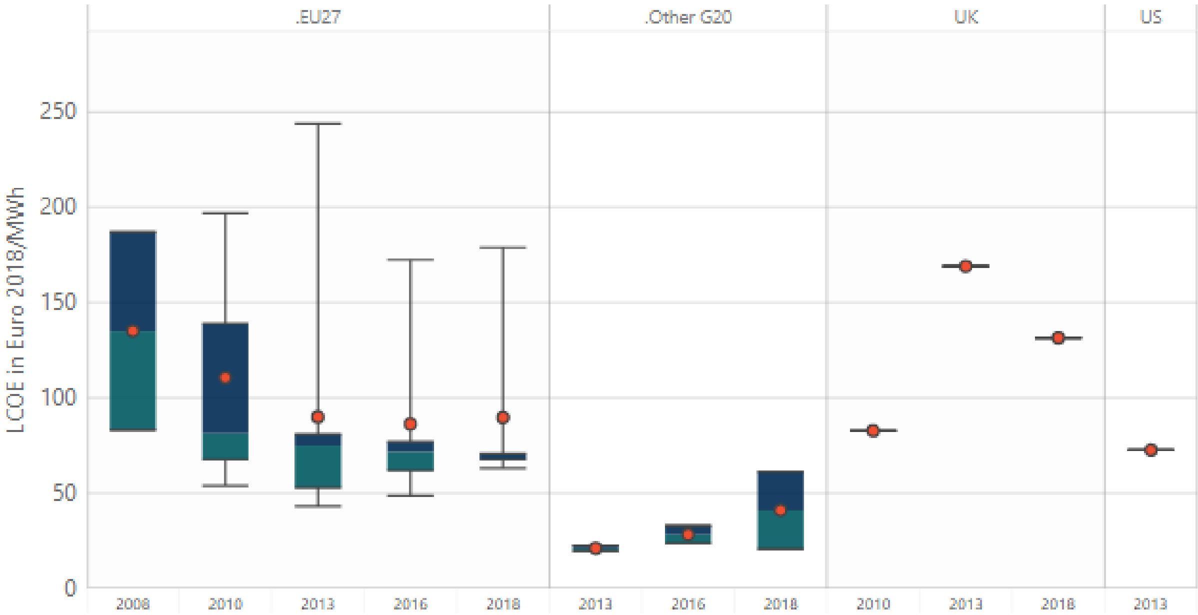
Source: Authors' elaboration.

1.3.8 Biogas

LCOE for electricity from biogas-fired plants ranged between €64-180/MWh in the EU27 countries in 2018. These rates are much higher than those registered in other parts of the world mostly due to the scale of the power plant projects. EU27 data collection includes projects with installed capacities below 2 MW which register CAPEX levels (in 2018) that ranged from €1,700/kW to €15,000/kW (around €5,000/kW for most projects). Overall, costs have dropped by over 30% since 2008. In the UK costs were rather volatile reaching €130/MWh in 2018.

In G20 countries, biogas LCOE ranged between €20-60/MWh in 2018, and remained rather stable in the period at around €40/MWh. LCOE rates are much lower than those seen for EU27 and UK as projects range from 1 MW to 10 MW of installed capacity and CAPEX levels from €1,000/kW to €6,500/kW (around €3,900/kW for most projects). Observations only for India, Argentina, Mexico and the US are available.

Figure 1-23 LCOE results for EU27 and G20 - Biogas



Number of observations per year

Country group	2008	2010	2013	2016	2018	**Total**
EU27	3	5	10	8	10	**36**
G20		3	10	2	5	**20**

Source: Authors' elaboration.

1.3.9 *Marine Energy*

Global installed capacity of ocean and tidal power plants reached 535 MW in 2019 with 97% of this capacity being tidal barrages (EUSEW 2020).

According to Ocean Energy Europe (2020), in European countries, since 2010, 27.7 MW of tidal stream technology was deployed (10.4 MW are currently operational while 17.3 MW are decommissioned projects that completed testing programs) and 11.8 MW of wave (1.5 MW currently operational and 10.3 MW have been decommissioned). France and the UK are the main countries in Europe developing the technologies. In 2019, two high capacity (> 500 kW) tidal devices were deployed: the 1,000 kW Hydroquest Ocean by Hydroquest in Paimpol-Bréhat (France) and the 500 kW Deep Green 500[17] by Minesto in Holyhead Deep (Wales, UK). Outside Europe, more recent projects include the 1,250 kW OE35 wave energy device by Ocean Energy in Portland (US).

China and Canada are also investing in the technology and establishing support schemes to boost the industry. The Canadian province of Nova Scotia lured investments through a €350/MWh FiT scheme. Among those, is the 9 MW (6x1.5 MW) Uisce Tapa project by DP Energy SPVs Halagonia Tidal Energy Limited (HTEL) and Rio Fundo Operations Canada Limited (RFOCL) (DP energy 2020). The project was approved a CAD 530/MWh (€346/MWh) FiT for 15 years and is expected to be commissioned in January 2023. In 2019, China also started a FiT scheme for the technology at €330/MWh. Another significant project expected soon is the 40 MW Larantuka tidal power plant developed by Tidal Bridge (EUSEW 2020). The US$225m (€200m) project (around €5,000/kW) will be located in the Flores Timur, Nusa

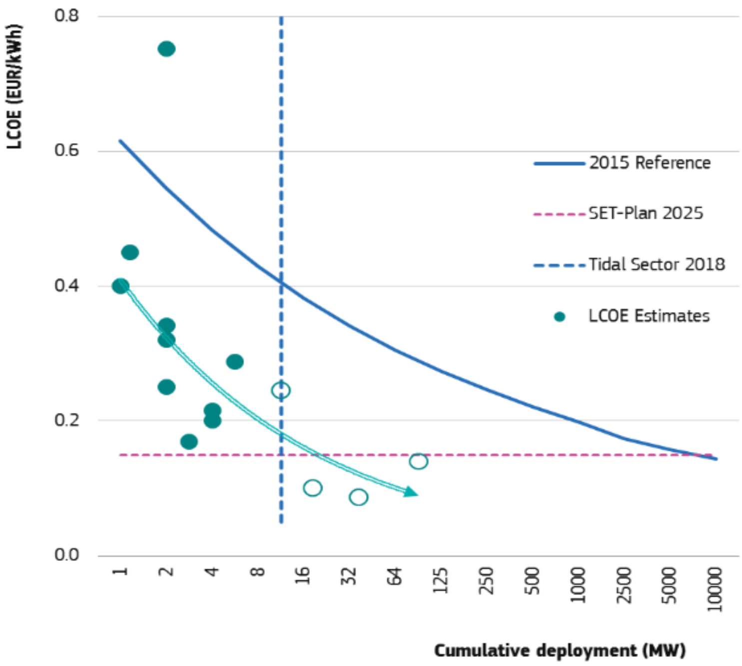
[17] €100m were invested in the project according to Minesto (i.e. €200,000/kW).

Tenggara Timur region (Indonesia) and despite being in early stages of development it is expected to be operational in the fourth quarter of 2022 (Tidal Bridge, 2020).

According to Magagna and Tacconi (2019) LCOE for tidal energy technology ranged between €340-380/MWh in 2018, a 40% reduction from 2015 levels, which were around €600/MWh[18].

Under the SET Plan (2018) released by Ocean Energy Europe targets to reduce the LCOE of ocean technology were set at €150/MWh for tidal stream by 2025 (and €100/MWh by 2030), and at €200/MWh for wave energy by 2025 (and €100/MWh by 2035). With these considerable cost reduction targets the project pipeline for marine energy projects is already starting to expand. According to EUSEW (2020) (IRENA estimates) the worldwide installed capacity of ocean and tidal power plants should reach 10 GW in 2030, with over half of it to be located in Europe.

Figure 1-24 LCOE estimates for marine energy technologies



Cost-reduction curves for tidal energy and LCOE estimates from ongoing projects. Solid dots represent data from ongoing demonstration projects, while hollow dots indicate developers' estimates on the basis of technology improvements and increased deployment.

Source: Joint Research Centre in Magagna and Tacconi (2019)

1.3.10 Natural Gas

In recent years with the drop in gas prices gas-fired installed capacity increased significantly and this trend can be expected to continue (see box below). The US has the largest gas-fired power plant fleet with 541 GW of installed capacity in 2018. The country also had the highest net capacity additions of all countries covered between 2008 and 2018 (+52 GW), followed by Russia (+34 GW) as well as South Korea (+19 GW), China (+18 GW) and Saudi Arabia (+18 GW). In Europe, the UK has the largest gas fleet, at 33 GW, followed by Spain at 32 GW.

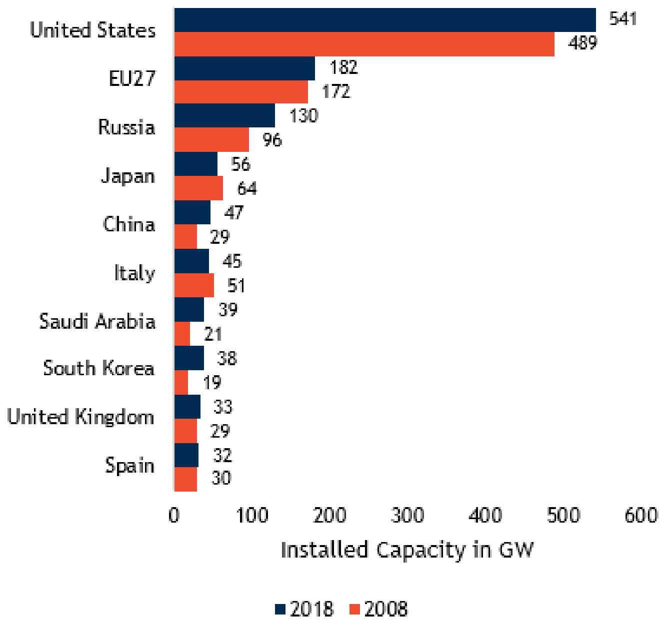
[18] JRC Calculation based on EC restricted data. Assumption: 12 % learning rate and 12 % discount rate (Magagna and Tacconi, 2019)

The gas boom in G20 countries

The gas boom witnessed in the US pushed for a decrease in coal consumption for power generation[19], stronger emissions standards and the availability of cheaper shale gas from its growing tight oil production[20] (Enerdata, 2019). On the other side of the globe, China is also turning to gas as a way to decrease air pollution from burning coal. The country's 13th Five-Year Plan states targets to increase the share of natural gas in the primary energy mix to 15% in 2030 (Enerdata, 2019).

A good indicator of the boom in gas markets worldwide is the development of LNG export and import terminals. In 2000, less than 6% of the total natural gas traded was LNG while in 2018 this share rose to 11% reaching over 430 bcm. The global LNG import capacity stood at around 800 bcm with another 500 bcm of capacity planned for development (26% of the project pipeline is in China and 12% in India). Meanwhile, the global LNG export capacity surpassed 400 bcm in 2019 with a project pipeline of over 800 bcm (mostly in the US, accounting for 40% of the project pipeline, and Canada, with 35%) (Global Energy Monitor, 2019).

Figure 1-25 Installed Capacity in 2018 - Gas-fired installed capacity (GW)



Source: Enerdata GED database.

Gas-fired power plants have power generation costs which depend strongly on fuel costs. For the calculation of LCOE in the EU27 and the UK for this power technology, fuel costs and carbon price estimates were provided by the EC from the EU Reference Scenario[21] from 2016. Data and projections were initially provided from 2015 until 2040 and have been adjusted according to actual average gas prices and prices registered from 2015 to 2018 (see further details in Annex A).

With these fuel cost and carbon price assumptions, LCOE estimates for CCGT power plants increased from €80/MWh in 2008 to €98/MWh in 2018 (+22%). Costs for new projects in 2018 ranged between €94

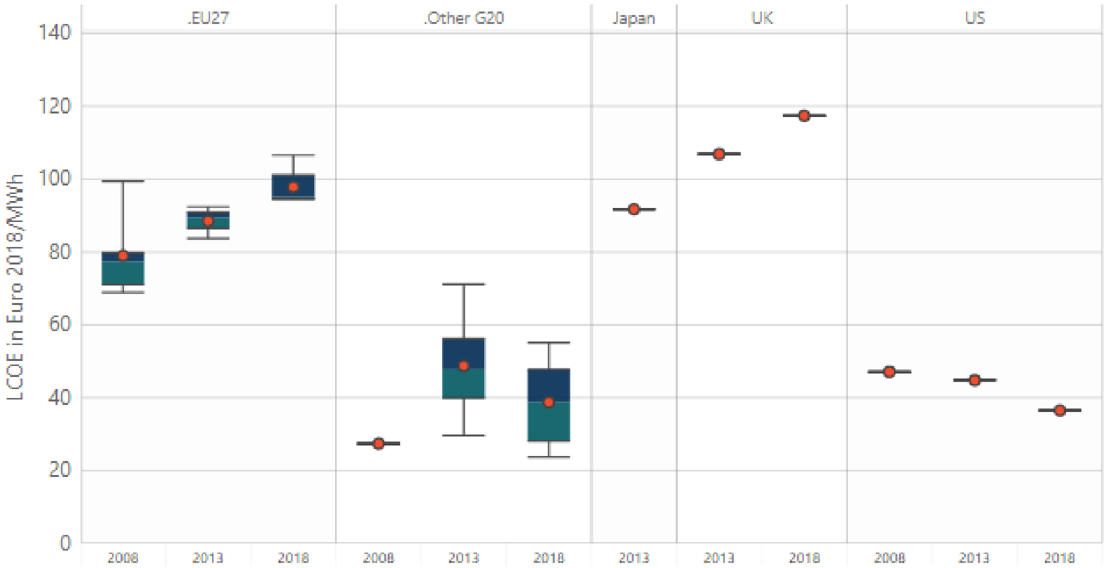
[19] In 2018, coal consumption reached is lowest level in 40 years. Up to 13 GW of coal-fired capacities were retired in 2018 and 14.5 GW of new gas-fired power capacity were added.
[20] The US became the world's largest gas producer in 2018.
[21] https://ec.europa.eu/energy/data-analysis/energy-modelling/eu-reference-scenario-2016_en

and 107/MWh. In the UK CCGT power plants has LCOE of €170/MWh in 2018 due to the country's very low utilisation rate.

OCGT LCOE in the EU27 were around €50-100/MWh in 2018 using the same gas prices and carbon costs, while in the UK they were at almost €100/MWh. With very few observations on OCGT, no trend over the period was derived.

For estimating LCOE of gas-fired technologies in the non-EU G20 countries, no carbon price assumptions were applied (explaining the difference when compared to EU27 cost estimates). Natural gas costs were provided by IEA's price database and, for Saudi Arabia and India, gas prices from the US Henry Hub were applied (for further details see Annex A). With most CCGT projects being commissioned in 2013, LCOE ranged between €30-90/MWh (most observations below €65/MWh) in that year. Data for 2018 indicate that LCOE dropped by around 25% in five years to values ranging between €24-55/MWh. This is mainly due to the recent worldwide drop in natural gas prices, which has led to higher development of power plants.

Figure 1-26 LCOE results for EU27 and G20 - Gas-fired power generation CCGT

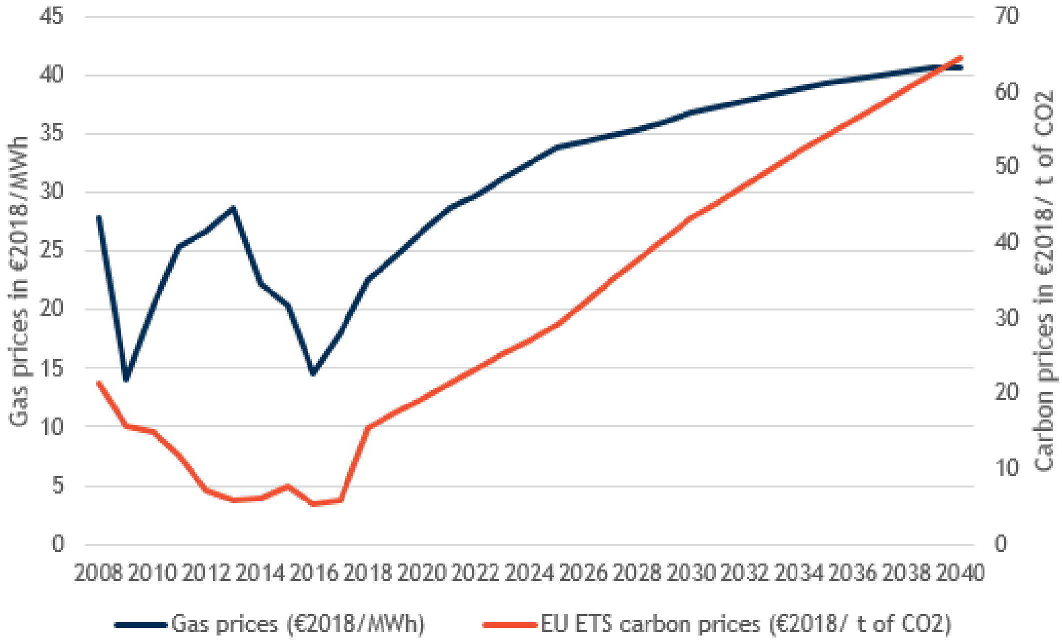


Number of observations per year

Country group	2008	2013	2018	**Total**
EU27	10	8	6	24
G20	4	16	14	34

Source: Authors' elaboration.

Figure 1-27 Gas prices and Carbon prices from 2008 to 2040 for EU27



Source: Authors' elaboration based on EC Reference scenario 2016 and actual gas and carbon prices registered from 2008 until 2018.

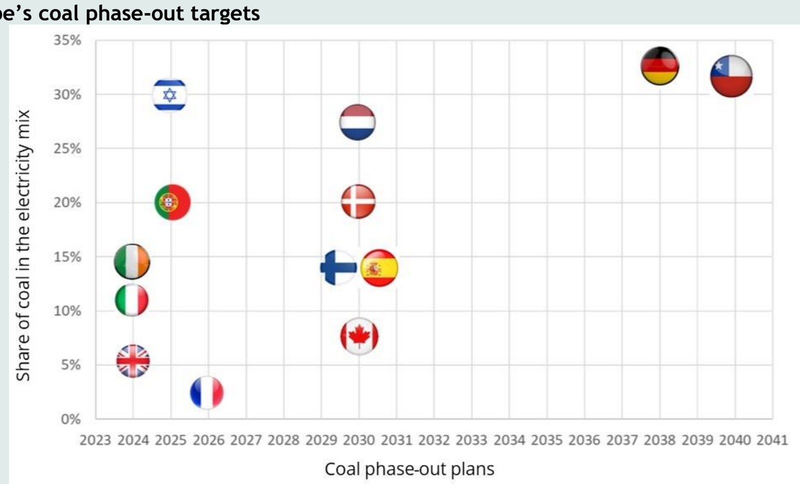
1.3.11Coal

With 1,118 GW in 2018, China has the largest fleet of coal-fired power statioins, followed by the US (263 GW) and India (227 GW). In terms of net capacity addition, China has added almost 570 GW of capacity between 2008 and 2018, and India has added 133 GW. The US registered a net reduction of its capacity since 2008 by 56 GW.

The coal phase-out and recent trends – EU and G20 countries

Coal consumption has been dropping in the EU due to climate policies, the development of renewables and gas-fired power plants, and an increase in the price per tonne of CO_2. So far, eight EU Member States have decided to phase out coal by 2030. Germany, which produces 1/3 of its electricity from coal (and contributed to 36% of the EU's power production from coal in 2018), approved a bill to exit coal by 2038 and close 40% of its coal capacity by 2030. Outside the EU, the UK has established its coal phase out for 2024.

Figure 1 - Europe's coal phase-out targets



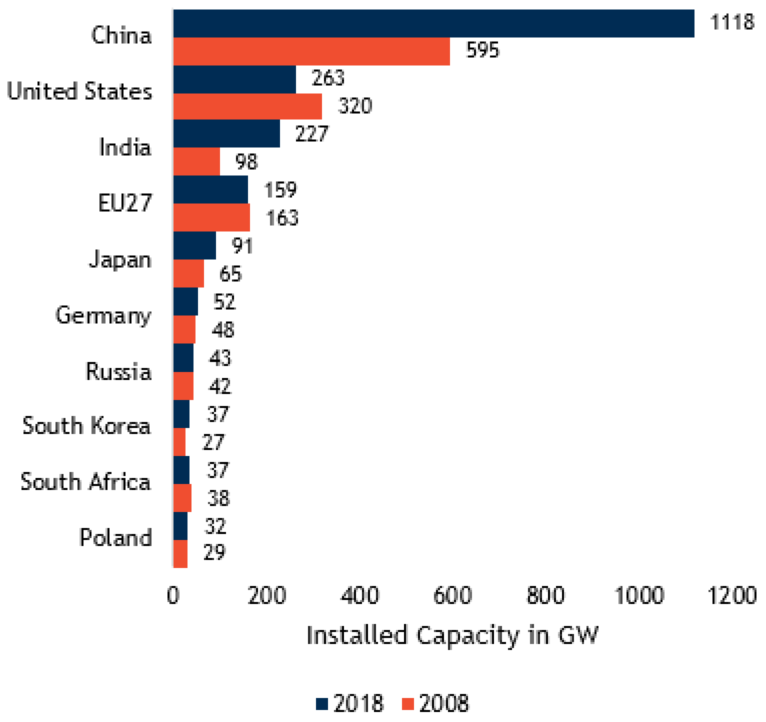
Source: Enerdata, 2020

Beyond coal-exit targets, a closer look at the status of projects under construction reveals a growing number of coal-fired power plant cancellations. Of the additional global capacity expected by 2030 (i.e. 300 GW), 21% is frozen or cancelled. Estimates show that over 40% of the global existing coal-fired power plant fleet is operating at a loss (with negative cash flows) and, of the project pipeline, many projects will enter the market with a negative cash flow pushed by regulatory and policy structures that favour coal power. Countries with the lowest level of coal-fired power profitability include China, EU countries and the US (Carbon Tracker, 2020).

In the US, coal consumption reached its lowest level in 40 years, due to capacity retirements (15 GW in 2018), stricter emission standards and the availability of cheaper gas. In parallel, India cancelled 46 GW of its coal-fired power project pipeline between January 2019 and January 2020. Which will most likely lead to capacity additions of 30 GW by 2030, half of the value expected by the Central Electricity Authority (CEA) (IEEFA, 2020). The amount of permits issued for new projects also decreased, from 58 GW in January 2019 to 29 GW in January 2020.

Meanwhile, China seems to go on a different direction. The government cleared 6.6 GW of new coal-fired capacity for construction in March 2020 (more than the 6.3 GW registered during the entire year of 2019) (Enerdata, 2020b). Recent regulations already approved more relaxation on new coal-fired construction permitting and the government is looking to prioritize economic growth (i.e. boost coal development if needed). The operating fleet, however, seems to be saturated with the average availability factor of coal-fired units at 6,570 hours, but actual utilization rates reaching only 4,724 hours in 2018 (4,762 hours for supercritical facilities) (Enerdata, 2020c).

Figure 1-28 Installed Capacity in 2018 - Coal-fired installed capacity (GW)



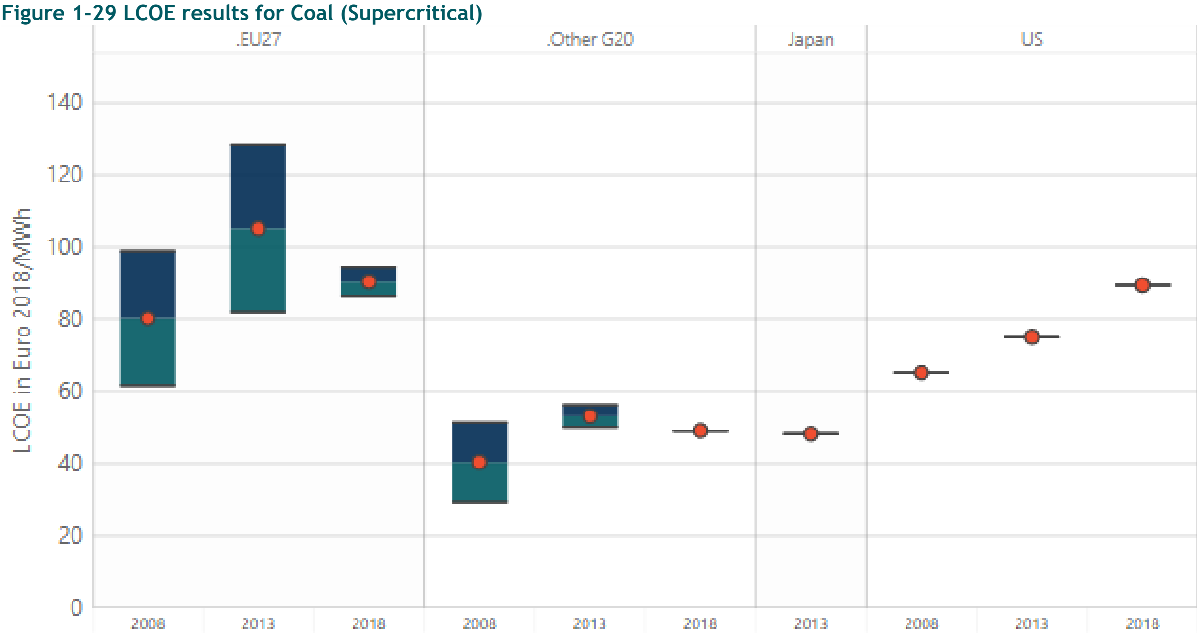
Source: Enerdata GED database.

Coal-fired power plants have power generation costs sensitive to fuel costs. For the calculation of LCOE in the EU27 and the UK for this energy source, fuel costs and carbon price estimates were provided by the EC from the EU Reference Scenario[22] of 2016. Data were initially provided from 2015 until 2040 and have been adjusted according to actual average coal prices and carbon prices registered from 2015 to 2018 (see further details in Annex A).

With these fuel costs and carbon prices, LCOE estimates for IGCC projects (data collected from the UK only) were around €104/MWh in 2013, and for subcritical projects (data collected from Poland only using a national source) were around €105/MWh in 2018. There weren't enough observations to derive a trend for these technologies.

The 19 supercritical coal-fired power plants from the database present a soft increasing trend from 2008 to 2018 going from €80/MWh to €90/MWh. In 2018, LCOE ranged between €85-95/MWh.

Figure 1-29 LCOE results for Coal (Supercritical)



Number of observations per year

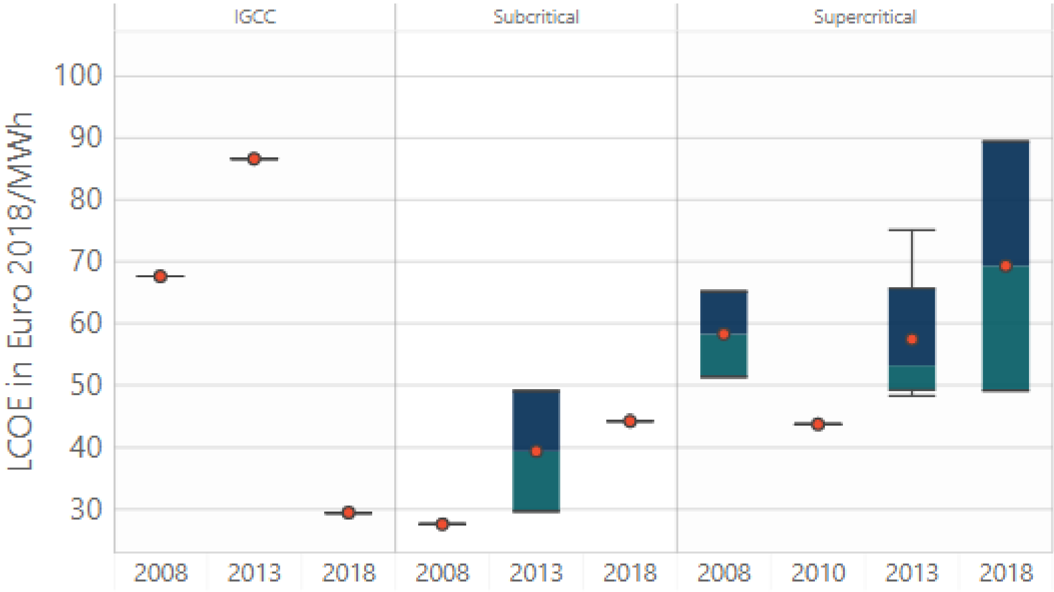
Country group	2008	2013	2018	**Total**
EU27	2	3	4	**9**
G20	7	8	4	**19**

Source: Authors' elaboration.

Costs for coal technologies in the G20 countries were estimated using the international coal market prices (for further details see Annex A) and no assumptions were included regarding carbon costs. IGCC technologies are observed only in the US with LCOE around €85/MWh in 2013. Subcritical technologies have much lower costs at around €40/MWh in 2013 and €45/MWh in 2018 (data from India and Turkey). LCOE of supercritical power plants (data from Japan, the US, Canada and Turkey) have increased by 16% since 2008, reaching €70/MWh in 2018.

[22] https://ec.europa.eu/energy/data-analysis/energy-modelling/eu-reference-scenario-2016_en

Figure 1-30 LCOE results for G20 - Coal (IGCC and Subcritical vs Supercritical)



Number of observations per year

Technology	2008	2010	2013	2018	**Total**
IGCC	3		3	1	**7**
Subcritical	1		2	1	**4**
Supercritical	6	1	8	4	**19**

Source: Authors' elaboration.

1.3.12 Nuclear

The US has the largest nuclear power plant fleet with 104 GW in 2018, followed by France (63 GW), China (45 GW), Japan (37 GW) and Russia (29 GW). Between 2008 and 2018, net capacity additions in China totalled 36 GW, Russia added 7.4 GW and South Korea 4.1 GW.

No datapoints for nuclear power were calculated for EU27 countries as although construction work on new plants is ongoing in Finland, France and the UK, there have been no new nuclear power plants commissioned between 2008 and 2018. Because China is the largest market for the technology, the timeframe was enlarged to cover as many projects as possible. Due to the very low level of transparency regarding nuclear costs in all countries, we only retained very few reliable datapoints.

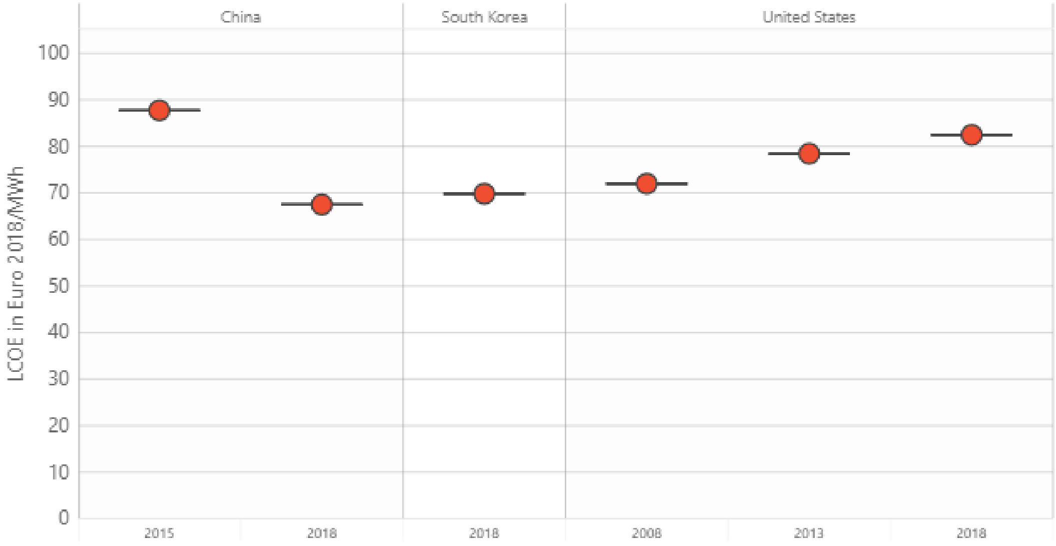
For this technology fuel costs are estimated to be around €10/MWh based on OECD's publications[23].

For the US LCOE levels were €72/MWh in 2008 and €82/MWh in 2018. In 2018, CAPEX levels of €5,250/kW are compensated by high capacity factors (93%). Costs in the US increased by 14% between 2008 and 2018.

China is the largest market in terms of nuclear development in the period. For this country the scope was extended to include 2015 data. Data from Enerdata's Power Plant Tracker database shows that average CAPEX levels decreased from €4,200/kW in 2015 to €2,800/kW in 2018, leading to LCOE of €67/MWh in 2018, the lowest in the G20 countries where reliable data was available.

[23] OECD, 2015 https://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf.

Figure 1-31 LCOE results for G20 - Nuclear

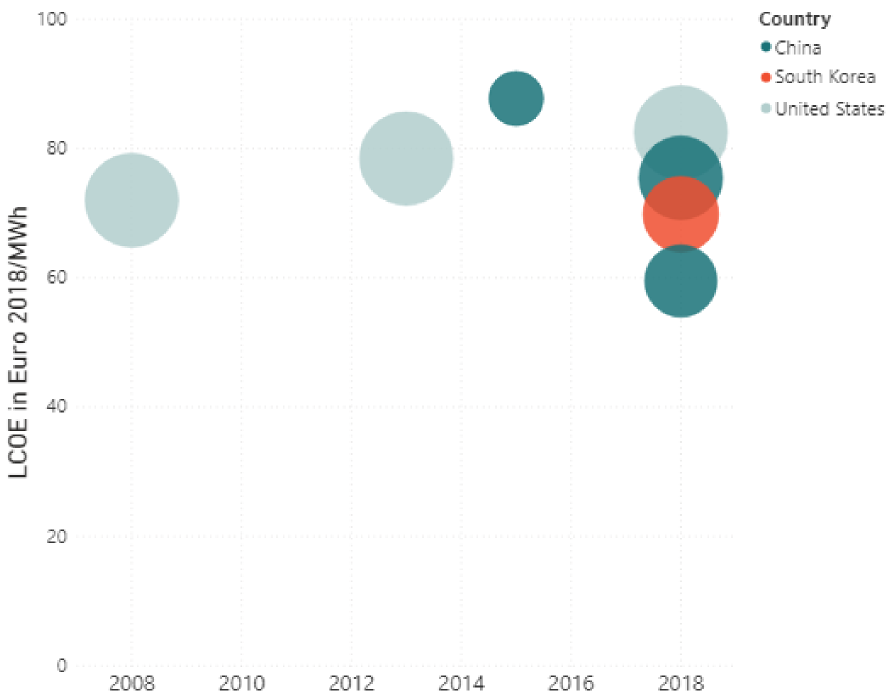


Number of observations per year

Country group	2008	2013	2015	2018	**Total**
G20	1	1	1	6	**9**

Source: Authors' elaboration.

Figure 1-32 LCOE results for Nuclear projects by Installed Capacity



Projects range from 650 MW to 2,300 MW (bubble size)

Source: Authors' elaboration.

Long-term operation of existing Nuclear power plants

Whilst new nuclear power plants have not been commissioned in Europe recently, there remains significant ongoing investment in nuclear power, not only in a new fleet of plants being constructed in Finland, France and the UK but also through refurbishments and the granting of operational license renewal to existing power plants thus extending their lifespan to as long as 80 years.

Extending the lifetime of nuclear power plants affects operation and maintenance strategies, decommissioning schedule and strategy, radioactive waste management and disposal requirements, fuel characteristic modifications, and a country's overall nuclear energy programme (OECD NEA, 2007). European countries with power plants already operating past their initial designed life include Belgium, Czech Republic, Finland, France, Hungary, Netherlands, Romania, Spain, Slovenia, Sweden, , and the UK. Despite refurbishment works being rather common, data on investment costs spectific to these projects are rarely disclosed. For this, LCOE estimates for the refurbishment of nuclear power plants could not be calculated, but the following example sheds some light on costs.

Illustrative recent license renewals

In May 2020, Spain's Nuclear Safety Council (CSN) granted life extension to the Almaraz nuclear power plant (owned by Iberdrola, Endesa and Naturgy) until 2027-2028. The Almaraz power plant is the oldest in Spain with reactors commissioned in 1981 and 1983 (1 GW each). The plant's shareholders have agreed to invest €600m to reach long-term operation (Nuclear engineering, 2020). In September 2019, French EDF annouced plans to invest €2.1bn to extend the lifetime of its Bugey nuclear power plant that includes four reactors totalling 3,580 MW (2 x 910 MW and 2 x 880 MW) (EDF, 2019).

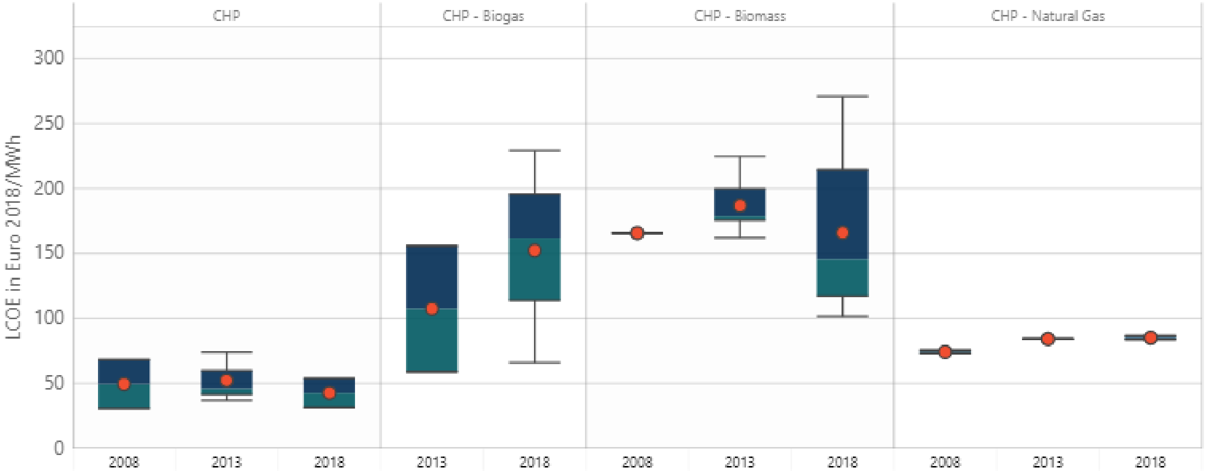
1.3.13 Combined heat and power (CHP)

Data collection for CHP include power plants using different fuel types, biogas, biomass, and natural gas. Some expert submission did not provide the fuel type used in the facility, so fuel costs weren't incorporated in the calculation. For this technology the costs are calculated for electricity and heat using the overall efficiency rate of fuel use. This means that costs presented here represent the costs of unit of energy (electricity and heat) produced by the system (in MWh).

In the EU27, LCOE for CHP power plants of undetermined fuel remained rather stable since 2008 at around €50/MWh. With very few observations, power plants fuelled with biogas presented costs that ranged between €65-230/MWh in 2018. The cost of CHP power plants fired with biomass (wood) remained stable since 2008 and ranged between €101-270/MWh in 2018. Gas-fired CHP plants have increasing costs from €74/MWh in 2008 to €85/MWh in 2018.

In the UK biogas-fired CHP plants registered costs at €156/MWh in 2013 and €162/MWh in 2018, while biomass-fired CHP plants registered costs at €198/MWh in 2008 and €270/MWh in 2018.

Figure 1-33 LCOE&LCOH results for EU27 - CHP (Natural gas, biofuels and undetermined fuels)



Number of observations per year

Technology	2008	2013	2018	Total
CHP	2	3	2	7
CHP - Biogas		2	6	8
CHP - Biomass	2	15	17	34
CHP - Natural Gas	2	5	4	11

Source: Authors' elaboration.

1.3.14Domestic systems

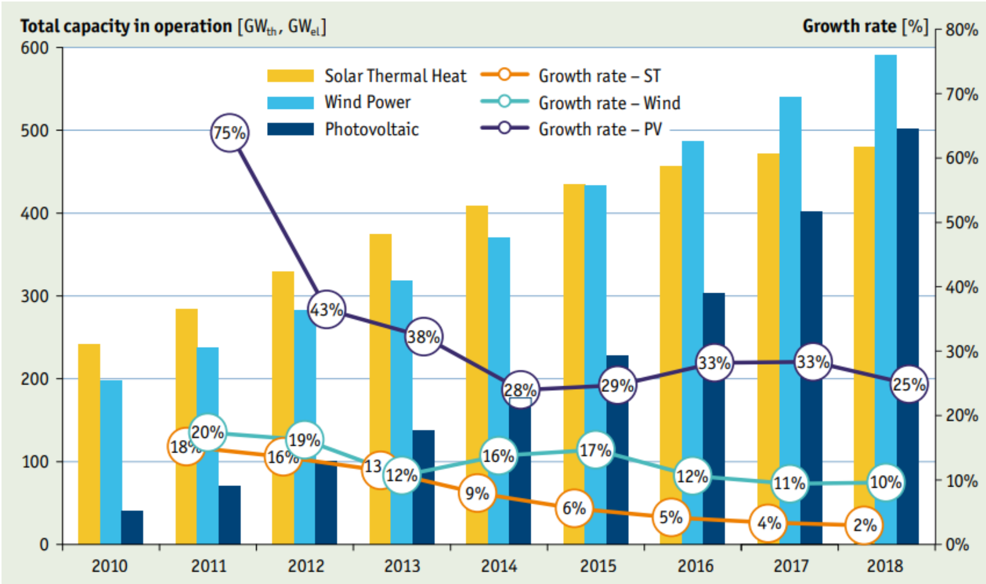
In this section, LCOH results represent the costs for generating heat from the following domestic systems: solar thermal, heat pumps, gas boilers and wood pellet boilers. With the exception of domestic solar thermal, data are only available for the EU27.

Domestic solar thermal

The total solar thermal capacity operational in 2018 was of 686 million m² (around 480 GW), almost 8 times more that 2000 levels (IEA SCH, 2019). Despite these developments this technology is loosing market shares to heat pumps and solar PV domestic systems[24], especially in Europe and China (traditionally the largest markets for solar thermal accounting for 82% of the global total capacity[25]). Denmark is the leading country in terms of installed capacity and capacity additions in Europe. In 2018, Denmark added 66,800 m², Germany added 9,380 m², and Austria 3,010 m².

[24] Thermal solar was the third RES after biomass and hydropower. Wind capacity surpassed that of solar thermal in 2016 and solar PV surpassed it in 2018.
[25] Installed capacity in China was of 334 GW and in Europe it was of 54 GW (2018)

Figure 1-34 World installed capacity and growth of solar thermal and other RES

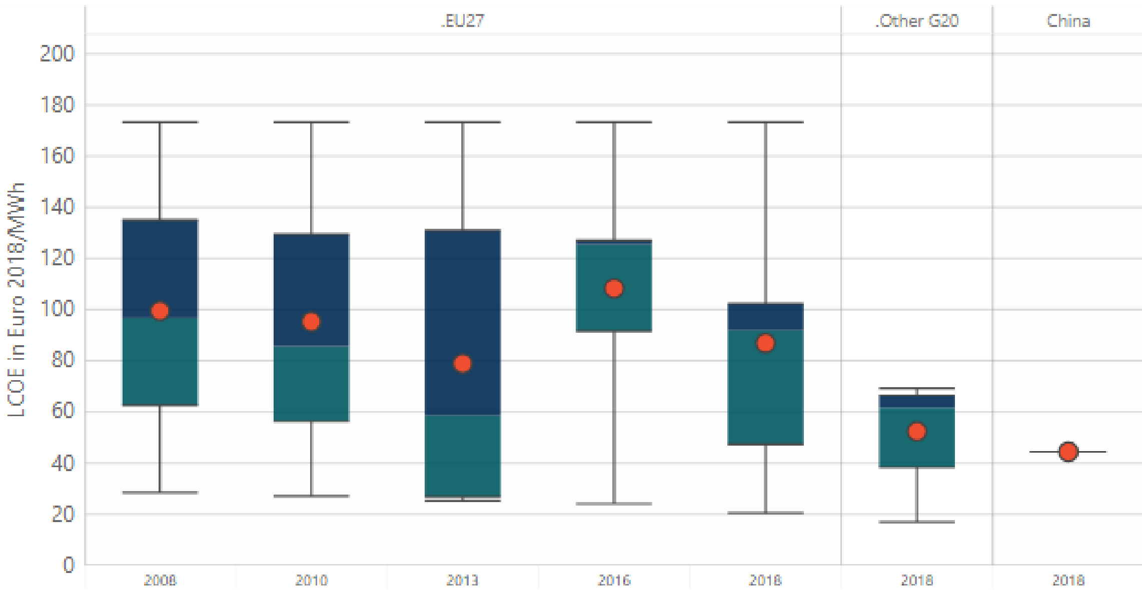


Source: IEA SCH, Solar Heat Worldwide 2019, page 10

Heat generation costs for domestic solar thermal in the EU27 countries have dropped 12% since 2008. In 2018, costs ranged between €20 and 173/MWh, with 75% of values being under €102/MWh. Overall costs of domestic solar systems (including installation) ranged between €600-1,000/m2 (1st and 3rd quartile).

LCOH in the other G20 countries were found only for 2018. In that year, they ranged between €20-70/MWh, with 75% of values being under €64/MWh.

Figure 1-35 LCOH results for EU27 and G20 - Domestic solar thermal



Number of observations per year

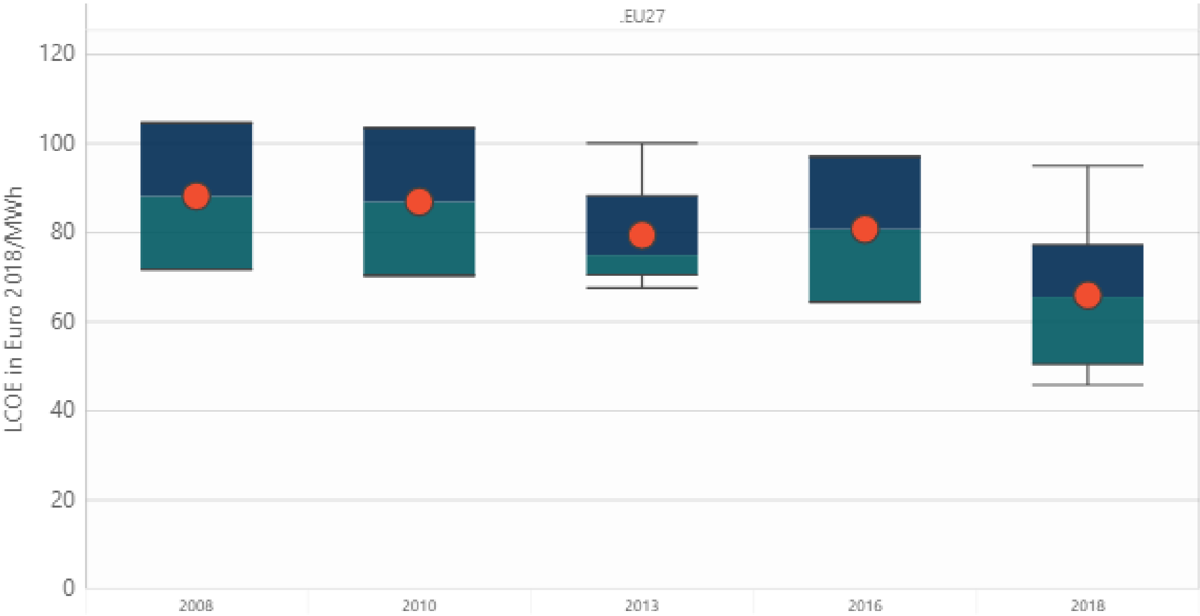
Country group	2008	2010	2013	2016	2018	Total
EU27	4	4	7	9	26	43
G20					42	42

Source: Authors' elaboration.

Domestic wood pellet boiler

In the EU27, domestic wood pellet boiler costs have dropped by 25%, between 2008 and 2018. In 2018, costs ranged between €45-95/MWh, with most values below €77/MWh. Overall costs of domestic boilers (including installation) ranged between €200-600/kW (1st and 3rd quartile).

Figure 1-36 LCOH results for EU27 - Domestic wood pellet boiler



Number of observations per year

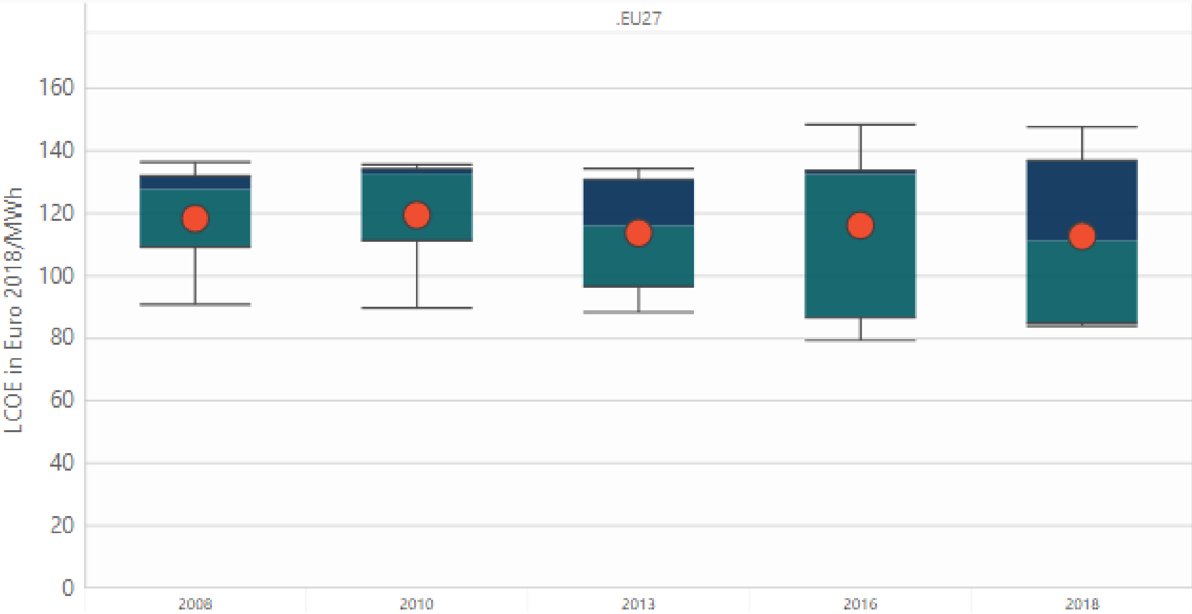
Country group	2008	2010	2013	2016	2018	**Total**
EU27	3	3	8	3	16	33

Source: Authors' elaboration.

Domestic heat pump

LCOH estimates for domestic heat pumps were calculated using the average electricity costs of EU27 countries (data from Eurostat). Costs slightly dropped in the period, ranging between €84-145/MWh in 2018, with most values below €135/MWh. Overall costs of domestic heat pumps (including installation) ranged between €750-2,000/kW (1st and 3rd quartile).

Figure 1-37 LCOH results for EU27 - Domestic heat pump



Number of observations per year

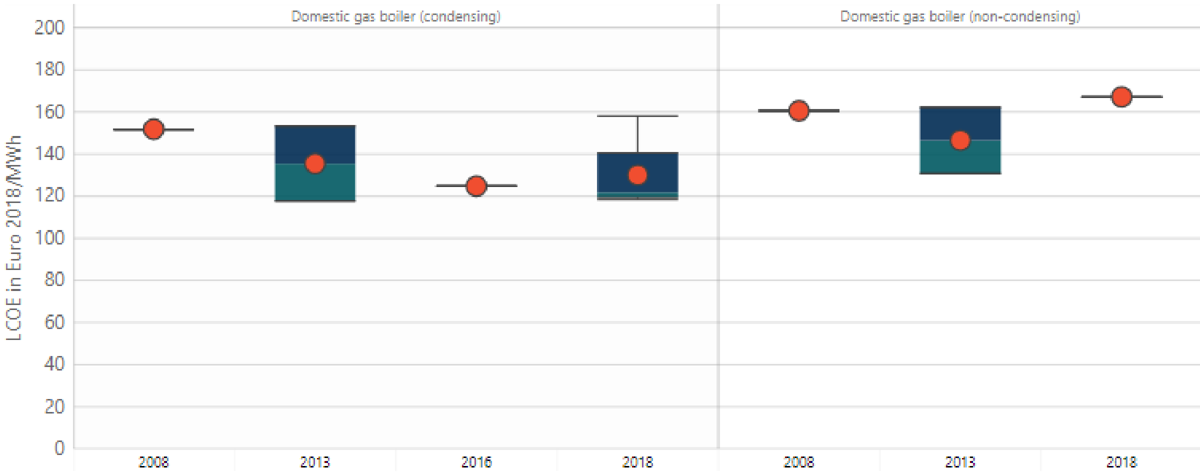
Country group	2008	2010	2013	2016	2018	**Total**
EU27	4	4	7	6	19	**40**

Source: Authors' elaboration.

Domestic gas boilers

With very few observations provided by country experts for domestic gas boilers, a trend cannot be derived for the period for EU27 countries. LCOH estimates, however, indicate that condensing systems are largely cheaper than non-condensing at €130/MWh compared to €170/MWh in 2018. Overall costs of domestic gas boilers (including installation) ranged between €100-175/kW (1st and 3rd quartile).

Figure 1-38 LCOH results for EU27 - Domestic gas boilers



Number of observations per year

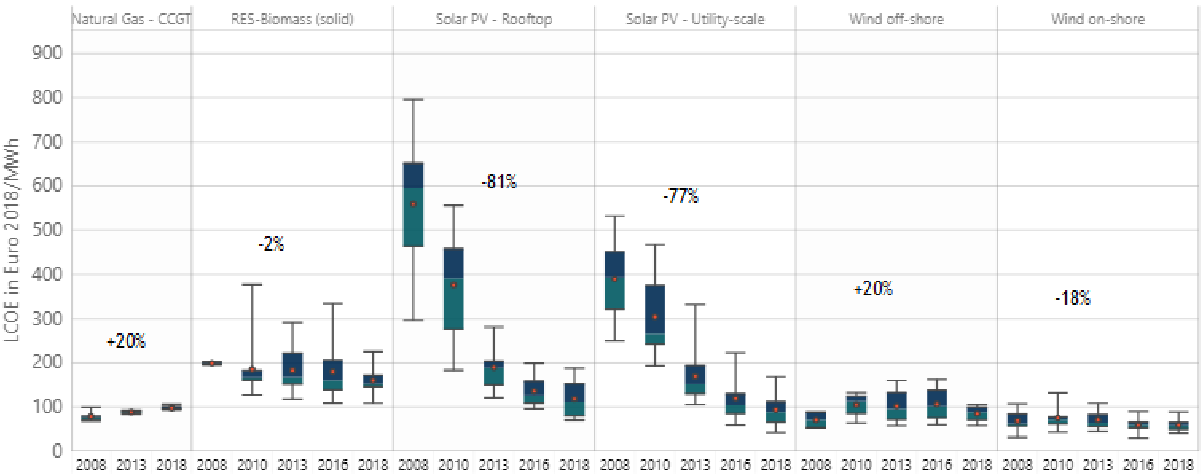
Technology	2008	2013	2016	2018	**Total**
Domestic gas boiler (condensing)	1	4	1	9	**15**
Domestic gas boiler (non-condensing)	1	4		1	**6**

Source: Authors' elaboration.

1.4 Cross-energy product cost analysis

In the EU27 countries, most RES have become cheaper than gas fired CCGT and supercritical coal power plants. In 2018, onshore wind LCOE were around €60/MWh, offshore wind around €85/MWh and utility-scale solar PV around €87/MWh. Despite the reduction of gas prices, CCGT power plants present LCOEs around €95/MWh (20% higher than 2008 costs) while coal-fired power plants have costs around €90MWh (12% higher than 2008 costs). Multiple aspects explain this: as the EU has established carbon prices, fossil fuel based generation costs have increased. This is not, however, the main reason why renewables have gained so much in terms of costs. RES technology advancements and production in large scale have driven CAPEX costs down significantly since 2008. For solar PV for instance, the large-scale production of panels and modules have resulted in significant cost reductions of components. In the case of wind, the use of larger turbines has enabled power plants to increase capacity factors over time. It is worth mentioning that the multiple support schemes set in place have succeed in boosting demand for renewables, thus creating the mass markets instrumental for the steep cost reductions observed (and ongoing).

Figure 1-39 LCOE results for EU27 – main technologies comparison



Number of observations per year

Country group	2008	2010	2013	2016	2018	Total
EU27	92	117	171	141	147	668

Source: Authors' elaboration.

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Annex A - Methodology note

Expert submission provided CAPEX levels for different technologies paired with some additional LCOE composing variables. Sometimes, however, additional estimates were necessary to fill in the gaps in O&M costs, load factors and other variables. The estimates used to fill in those gaps are described in this Annex. To see which estimates contribute to each observation, please see the references listed in the Excel database provide with this report.

Asset's lifetime

The asset's lifetime is common across countries as it is considered that the technology has global diffusion throughout the world. For each technology, the lifetimes used are provided by the ASSET (2018) report, as the table below shows.

Sub-Energy	Technology	Project lifetime
FF-Coal / Lignite	Coal/Lignite	40
FF-Natural gas	CCGT and OCGT	30
Nuclear	Nuclear	60
RES-Biogas	RES-Biogas & Biomass	25
RES-Solar	Solar concentrated solar power (CSP)	25
RES-Solar	Solar PV - Rooftop	25
RES-Solar	Solar PV - Utility-scale	25
RES-Wind	Wind off-shore	25
RES-Wind	Wind on-shore	25
RES-Hydro	Hydropower	50
n.a.	Domestic heating systems	25

Capacity Factor

This variable is country, technology and year specific. When experts couldn't provide data, gaps in the capacity factor column were filled-in using the country and year specific average of expert data submission and/or IRENA data. In some cases, an average for all expert submitted data for the region was required in order to produce data for one country (this occurred for technologies where data coverage was scarce). In these and other cases, the main assumptions retained were as follows:

Country	Technology	Capacity factor	Source
EU27 & UK	Solar PV	9-14%	ENSPRESSO JRC open source
EU27&UK	Wind on-shore	23-36%	ENSPRESSO JRC open source
EU27&UK	Wind off-shore	34-49%	ENSPRESSO JRC open source
EU27&UK	Solar CSP	23%	ASSET (2018)
EU27&UK	Hydropower Run of River	22%	ASSET (2018)
EU27&UK	Coal-fired power plants	80%	ASSET (2018)
EU27&UK	CCGT	35%	ASSET (2018)
EU27&UK	Gas turbine with heat recovery	24%	ASSET (2018)
EU27&UK	Biomass (solid)	80%	ASSET (2018)

Country	Technology	Capacity factor	Source
EU27&UK	Biogas	77%	Average expert submission
Austria	Domestic solar thermal (in kWh/M2)	369-505 kWh/m2	IEA Solar Heat Worldwide (2018)
Germany	Domestic solar thermal (in kWh/M2)	378-421 kWh/m2	IEA Solar Heat Worldwide (2018)
EU27&UK	Domestic wood pellet boiler	14%	BEIS (2018)
EU27&UK	Biomass CHP Medium	70%	WEO (2016)
EU27&UK	Biomass CHP Small	70%	WEO (2016)
EU27&UK	Geothermal	85%	WEO (2016)
United States	Geothermal	80%	WEO (2016)
United States	Hydropower - large-scale	30%	WEO (2016)

Fixed O&M costs

The assumptions regarding FO&M were taken from publications as a function of the CAPEX level (% per year) and not in absolute values to maintain proportion. This variable is country and technology specific although in same cases regional assumptions were required. The main assumptions used were as follows:

Country	Technology	Fixed O&M (% of CAPEX/year)	Source
Africa	Solar photovoltaics - Rooftop	1%	WEO (2016)
Africa	Solar photovoltaics - Utility scale	1%	WEO (2016)
Africa	Wind offshore	4%	WEO (2016)
Africa	Wind onshore	3%	WEO (2016)
All	Biogas Anaerobic digester	2,3-7%	IRENA (2019)
All	Biogas Landfill gas	11-20%	IRENA (2019)
All	Biomass	2,1-3,2%	IRENA (2019)
All	Biomass STOKER/BFB/CFB BOILERS	3%	IRENA (2019)
All	Hydropower	2%	IRENA (2019)
Brazil	Biomass (solid)	4%	WEO (2016)
Brazil	CCGT	4%	WEO (2016)
Brazil	Hydropower - large-scale	3%	WEO (2016)
Brazil	Hydropower - small-scale	2%	WEO (2016)
Brazil	Nuclear	4%	WEO (2016)
Brazil	Solar photovoltaics - Rooftop	1%	WEO (2016)
Brazil	Solar photovoltaics - Utility scale	1%	WEO (2016)
Brazil	Wind offshore	4%	WEO (2016)
Brazil	Wind onshore	3%	WEO (2016)
China	Solar photovoltaics - Rooftop	1%	WEO (2016)
China	Solar photovoltaics - Utility scale	1%	WEO (2016)
China	Wind offshore	4%	WEO (2016)
China	Wind onshore	2%	WEO (2016)
Europe	Biogas	2%	ASSET (2018)
Europe	Biomass (solid)	4%	WEO (2016)
Europe	Biomass CHP Medium	4%	WEO (2016)
Europe	CCGT	1,8-2%	ASSET (2018)
Europe	Coal Subcritical	1,6-1,8%	ASSET (2018)
Europe	Coal Supercritical	2,3-2,4%	ASSET (2018)
Europe	Coal Ultrasupercritical	3%	WEO (2016)
Europe	Geothermal	1,9%-2,3%	ASSET (2018)
Europe	Hydropower - large-scale	3%	WEO (2016)
Europe	Hydropower - small-scale	2%	WEO (2016)
Europe	Nuclear	3%	WEO (2016)
Europe	Solar PV Rooftop	2%	ASSET (2018)

Country	Technology	Fixed O&M (% of CAPEX/year)	Source
Europe	Solar PV Utility scale	2%	ASSET (2018)
Europe	Wind offshore	2%	ASSET (2018)
Europe	Wind onshore	1%	ASSET (2018)
India	Solar photovoltaics - Rooftop	1%	WEO (2016)
India	Solar photovoltaics - Utility scale	1%	WEO (2016)
India	Wind offshore	4%	WEO (2016)
India	Wind onshore	3%	WEO (2016)
Japan	Solar photovoltaics - Rooftop	1%	WEO (2016)
Japan	Solar photovoltaics - Utility scale	1%	WEO (2016)
Japan	Wind offshore	4%	WEO (2016)
Japan	Wind onshore	3%	WEO (2016)
Middle East	CCGT	4%	WEO (2016)
Middle East	Gas turbine	6%	WEO (2016)
Middle East	Wind offshore	4%	WEO (2016)
Middle East	Wind onshore	2%	WEO (2016)
Russia	CCGT	4%	WEO (2016)
Russia	Gas turbine	6%	WEO (2016)
Russia	Wind offshore	3%	WEO (2016)
Russia	Wind onshore	3%	WEO (2016)
United States	CCGT	3%	WEO (2016)
United States	Geothermal	2%	WEO (2016)
United States	Hydropower - large-scale	3%	WEO (2016)
United States	Hydropower - small-scale	2%	WEO (2016)
United States	Solar photovoltaics - Rooftop	1%	WEO (2016)
United States	Solar photovoltaics - Utility scale	1%	WEO (2016)
United States	Wind offshore	3%	WEO (2016)
United States	Wind onshore	3%	WEO (2016)
World	Domestic solar thermal	0,25-0,5%	IEA Solar Heat Worldwide (2018)

Variable O&M costs non-fuel

For wind onshore generation assumptions from IRENA (2019) were used rather than from ASSET (2018) as the former correspond to actual projects. The same was taken into consideration for solid Biomass projects. Solar PV and Hydropower assumptions from ASSET (2018) were also applied on other G20 countries when no other reference was available.

Main assumption regarding VO&M were as follows:

Country	Technology	Variable O&M (euro/MWh)	Source
All	Biomass	3.96	IRENA (2019)
All	Wind onshore	0.02	IRENA (2019)
Austria	Wind onshore	0.03	IRENA (2019)
Denmark	Wind onshore	0.02	IRENA (2019)
EU27&UK	Biogas	2.56	ASSET (2018)
EU27&UK	CCGT	2.31-1.99	ASSET (2018)
EU27&UK	Coal-fired Subcritical	2.4-3	ASSET (2018)
EU27&UK	Coal-fired Supercritical	3.63-4.16	ASSET (2018)
EU27&UK	Geothermal High Enthalpy	0.32	ASSET (2018)
EU27&UK	Geothermal Medium Enthalpy	0.32	ASSET (2018)
EU27&UK	Hydropower Run of River	0.00	ASSET (2018)
EU27&UK	Nuclear	6.40	ASSET (2018)
EU27&UK	Solar CSP	0.10	ASSET (2018)
EU27&UK	Solar PV	0.00	ASSET (2018)

EU27&UK	Wind Offshore	0.39	ASSET (2018)
Germany	Wind onshore	0.03	IRENA (2019)
Spain	Wind onshore	0.03	IRENA (2019)
Sweden	Wind onshore	0.03	IRENA (2019)
The Netherlands	Wind onshore	0.01	IRENA (2019)

Fuel use Efficiency

For solar technologies (Solar PV - Utility-scale; Solar PV – Rooftop; Solar concentrated solar power (CSP); Domestic solar thermal) wind (Wind on-shore; Wind off-shore), geothermal and hydropower (Hydro ≤ 10 MW; Hydro > 10 MW) the fuel efficiency is not relevant as the costs of fuel are considered zero. Combined heat and power technologies use overall efficiency rate leading to costs results for all the energy output (heat and power) with no differentiation.

Efficiency assumptions were considered as follows:

Country	Technology	Efficiency rate*	Source
EU27&UK	Coal-fired Subcritical	37-38%	ASSET (2018)
EU27&UK	Coal-fired Supercritical	41-45%	ASSET (2018)
EU27&UK	Gas-fired - CCGT	57-60%	ASSET (2018)
EU27&UK	Biomass (solid)	27-35%	ASSET (2018)
EU27&UK	Biogas	38%	ASSET (2018)
All	Natural Gas - CHP	79-82%	WEO (2016)
All	Biogas - CHP	35%	Average expert data
All	CHP	79%	Average expert data
EU27&UK	Domestic gas boiler (condensing)	96%	Average expert data
EU27&UK	Domestic heat pumps	330%	Average expert data
EU27&UK	Domestic wood pellet boiler	82%	Average expert data
India	Coal-fired Subcritical	36%	WEO (2016)
United States	Coal-fired Supercritical	43%	WEO (2016)
United States	Coal-fired IGCC	44%	WEO (2016)
United States	Gas-fired - CCGT	59%	WEO (2016)
Brazil	Gas-fired - CCGT	58%	WEO (2016)
World	Biomass (solid)	35%	WEO (2016)
World	Biomass CHP Medium	70%	WEO (2016)
World	Biomass CHP Small	65%	WEO (2016)

**values over 100% are Coefficient of Performance (CoP) (mostly for domestic heat production systems).*

Fuel costs

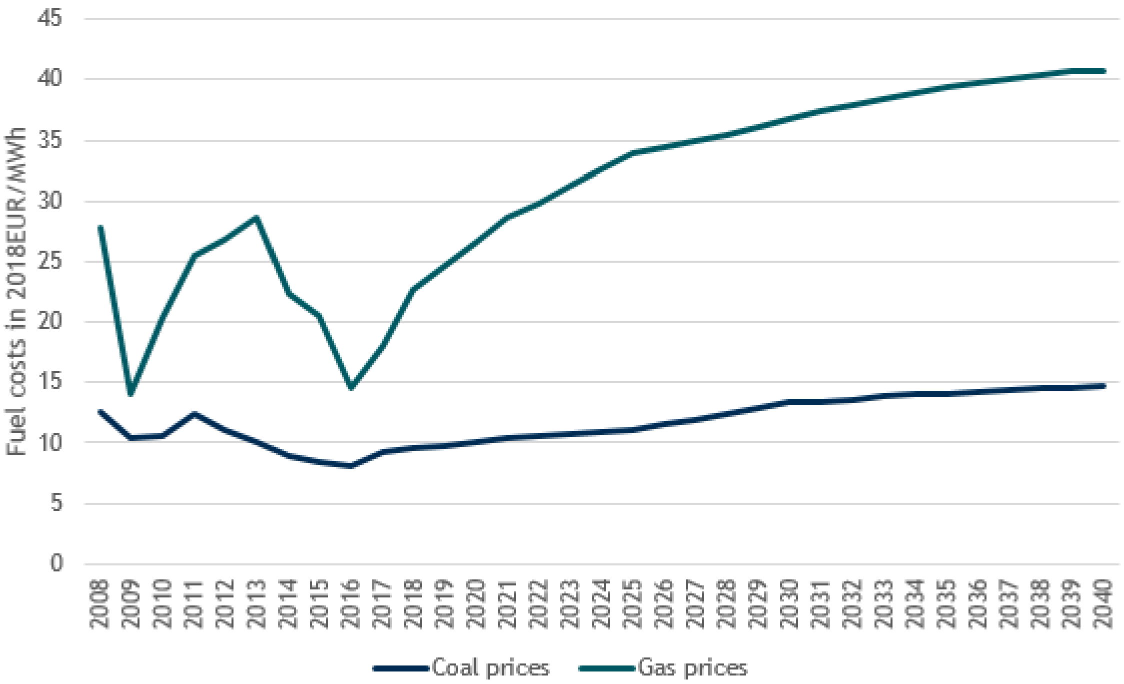
Fuel cost is a relevant variable for biomass (solid wood), coal-fired, gas-fired and domestic systems (except solar thermal). As detailed fuel costs for nuclear power plants weren't available and because the portion of such costs in the LCOE relatively small compared to investment costs and fixed O&M costs, no assumption regarding fuel costs for this technology have been incorporated in our calculations.

Projections on gas and coal prices were incorporated only for the EU27 and the UK in order to comply with the EC's 2016 reference scenarios. For all other technologies and regions, no projections were made. In other words, except for gas and coal, fuel costs in the EU27 and the UK from 2019 onwards (for projects with lifetimes going beyond 2018) remain stable at 2018 levels. For the G20 countries, no assumption on the projections of gas nor coal were incorporated either, i.e. from 2018 onwards coal are considered to remain stable at 2018 levels.

Natural Gas, Coal and Carbon prices in the EU27

For EU27 and the UK, natural gas prices and coal price estimates from 2008 until 2040 were based on two sources: Enerdata's Global Energy & CO2 Data database contributed to the actual European average prices until 2018; and, the EC's REF-2016 scenario provided estimates from 2019 onwards. As the REF-2016 scenario uses estimates from 2015, projections were adjusted to more recent price levels (keeping price evolution rates untouched).
The same approach and sources were used to estimate coal prices. As prices were expressed in currency/toe we used the conversion factor of 11,63 toe/MWh to obtain prices in terms of currency/MWh.

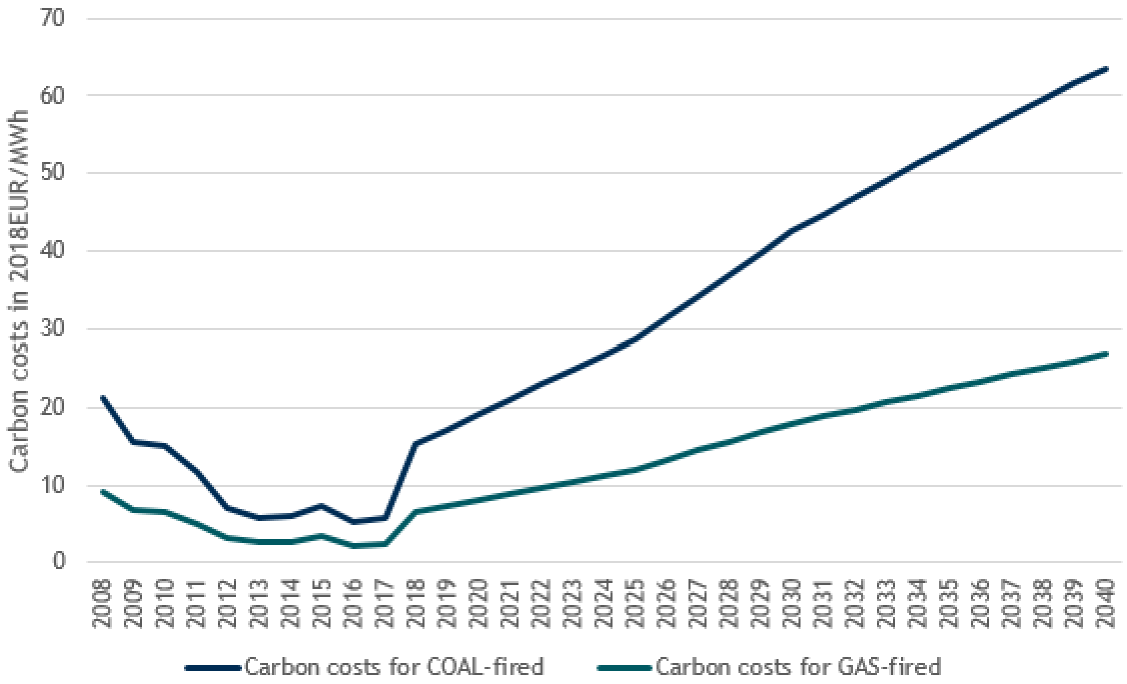
Figure A-1 Prices for coal and natural gas- EU27&UK



Source: based on Enerdata's Global Energy & CO2 Data database and EC's REF-2016 scenario

The REF-2016 scenario also provided carbon price estimates which were complemented with actual carbon prices in the EU Emissions Trading Scheme (ETS) from 2008 to 2018. As the REF-2016 scenario uses estimates from 2015, projections were adjusted to incorporate recent changes in carbon prices. Carbon prices for power generation assets were calculated using an "emission factor" by technology. For gas-fired power plants, for example, the registered emission level from gas-fired power generation was divided by the power output of the gas-fired power plant fleet. The so-called "emission factor" is the amount of emissions generated per MWh of power output. For gas-fired power plants, this emission factor is around 0.44 tCO_2/MWh, while for coal-fired power generation assets it is around 1 tCO_2/MWh.

Figure A-2 Carbon costs for coal-fired and gas-fired power - EU27&UK (€2018/MWh of electricity)



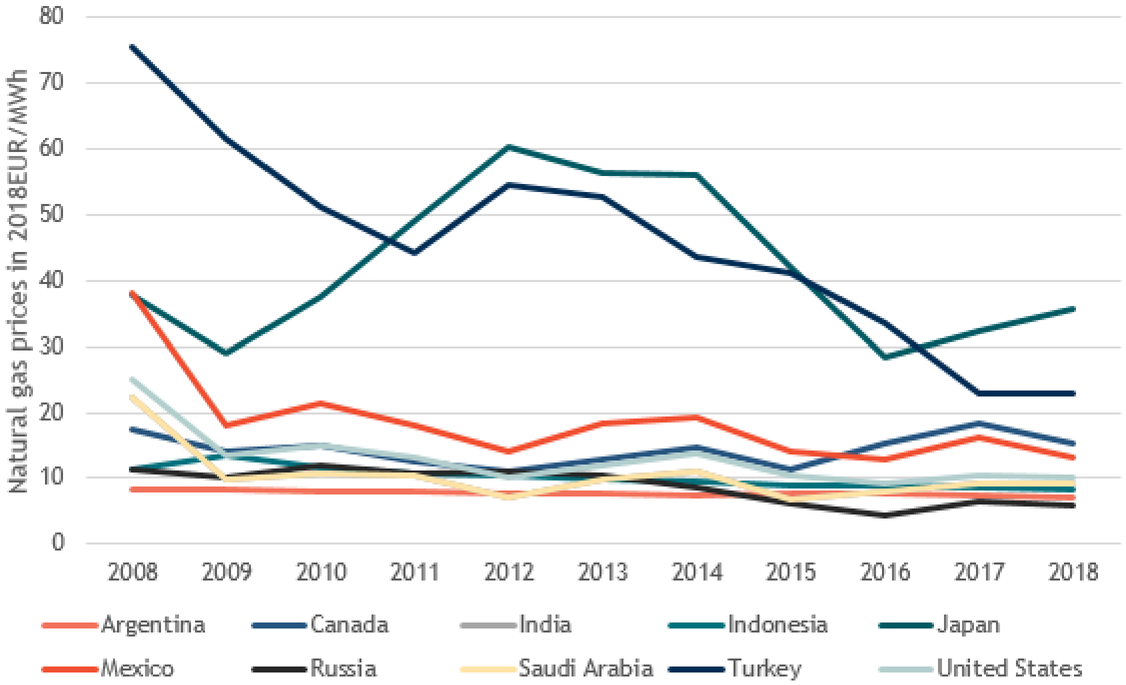
Source: based on Enerdata's Global Energy & CO2 Data database and EC's REF-2016 scenario

Natural Gas and Coal prices for non-EU G20 countries (except the UK)

Natural Gas

For estimating LCOE costs of gas-fired technologies in the G20 countries (except the UK), no carbon price assumptions were applied. Natural gas costs were provided by IEA's price database and, for India and Saudi Arabia, due to lack of data, the international gas prices from the US Henry Hub were applied. IEA's price database provides final prices paid for power generation. Furthermore, no projections on gas prices beyond 2018 were applied.

Figure A-3 Historical prices for natural gas for non-EU G20 countries (€2018/MWh of electricity)

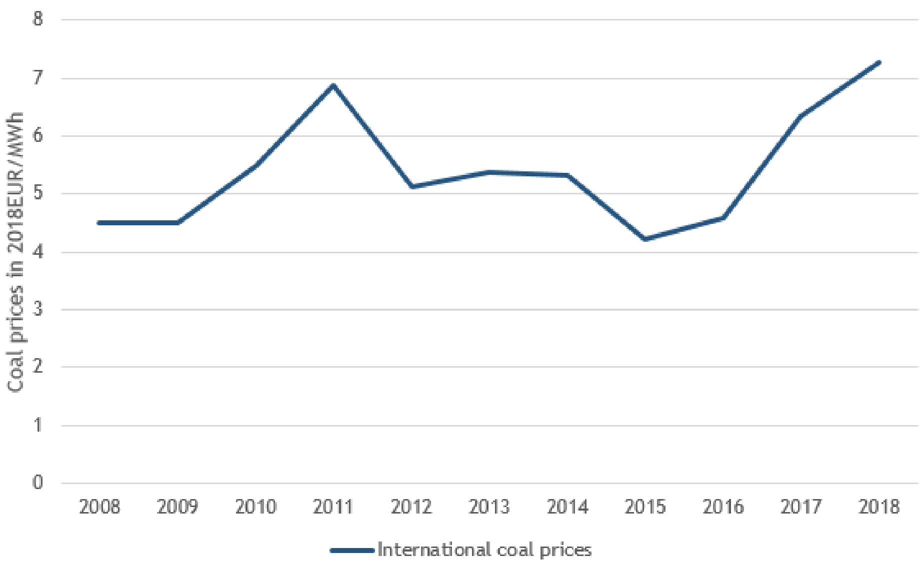


Source: IEA's price database (within Enerdata's Global Energy & CO2 Data database) and Yahoo finance (US Henry Hub)

Coal

LCOE for coal technologies in the G20 countries (except the UK) were estimated using the international coal market prices from Markets Insider[26] and no assumptions were included regarding carbon costs. Prices were initially provided in currency/ton and were converted to currency/MWh using a factor of 8.14 ton/MWh. Furthermore, no projections on coal prices beyond 2018 were applied.

Figure A-4 Prices for coal for non-EU G20 countries (€2018/MWh of electricity)



Source: Markets Insider Commodity prices

[26] https://markets.businessinsider.com/commodities/historical-prices/coal-price/usd/1.1.2008_31.12.2018 (accessed in March 2020)

Nuclear

Fuel costs for nuclear power generation data was provided from OECD's Projected Costs of Generating Electricity publications, which show a range between €9-11/MWh. The average fuel costs for nuclear power generation are thus considered to be €10/MWh for the entire database and include both front-end and waste management costs borne by the operator. No assumptions on the evolution of such costs beyond 2018 were made.

Biomass (solid wood)

Wood prices were obtained from the IEA Global Wood Pellet Industry and Trade Study 2017. The prices were converted from currency/ton to currency/MWh using the average heat content of dry wood of 5.5 MWh/t. An average for all EU27 and the UK was used, to keep an alignment with the approach proposed by the EC's REF-2016 scenario. For the years where data was lacking the closest data available was used as a proxy. For countries outside the EU27 (except the UK), the costs for wood from the US market, from the same publication, was used as a proxy as other cost information was not available. According to the sources, wood costs almost haven't changed in the period around €30-42/MWh in the EU27 and €23-28/MWh in the US.

Domestic systems fuelled with electricity

For domestic systems using electricity as fuel (Domestic heat pumps) data from Eurostat for European countries and Enerdata Global Energy & CO2 Data database (multisource) for non-European countries were used. The domestic power tariff applied for EU27 & UK calculations was an average of the region. The EU27 countries were not differentiated to keep an alignment with the approach proposed by the EC's REF-2016 scenario.

Domestic systems fuelled with natural gas

For domestic systems fuelled with natural gas, data from Enerdata Global Energy & CO2 Data database (multisource) were used. The domestic gas tariff applied for EU27 & UK calculations was an average of the region. The EU27 countries were not differentiated to keep an alignment with the approach proposed by the EC's REF-2016 scenario.

Domestic systems fuelled with wood

Wood prices were obtained from the IEA Global Wood Pellet Industry and Trade Study 2017. The prices were converted from currency/ton to currency/MWh using the average heat content of dry wood of 5.5 MWh/t. An average for all EU27 and the UK was used, to keep an alignment with the approach proposed by the EC's REF-2016 scenario. For the years where data were lacking the closest data available was used as a proxy.

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Annex B - Database construction

Data gathering and treatment

Main data sources

Data in the database is composed of three major sources, IRENA, Enerdata's Power Plant Tracker database and Expert Submission (multiple sources including data collect from industry players, Ministries, Energy agencies etc.). The contribution of these sources for Capex and capacity factor (main LCOE composing variables) are as follows:

Sources	CAPEX	Load Factor
Enerdata database	23%	n.a.
Expert submission	33%	30%
IRENA	45%	55%
ASSET (2018)	n.a.	10%
WEO (2016)	n.a.	3%
others	n.a.	2%
Total number of data points	**2900**	**2900**

Data validation and processing

We received 39 expert submissions from the 43 countries in the scope (missing data from Luxembourg, Malta, Indonesia, and South Africa). For these countries' other sources (IRENA and Enerdata's Power Plant Tracker) provided some information on costs.

Data processing and database construction

All data from mentioned sources and expert submission were inserted into a single Excel file. No estimates were used to estimate CAPEX levels while a set of assumptions was taken in consideration to fill-in the gaps and produce LCOE results (see Main Assumptions section of ANNEX A).

Data is, in most cases, technology and year specific. Considering that multiple sources contributed to the database construction, the same technology can present multiple observations for the same year (see example below). This allows for the creation of a LCOE range instead of a limited "average" value.

Country	Energy	Sub-energy	Technology	Year	CAPEX (EUR 2018/kW) (EUR/m2 for solar thermal)	Fixed OPEX (EUR 2018/kW) (EUR/m2/year for solar thermal)
Germany	Electricity	RES-Wind	Wind on-shore	2018	2,000	30
Germany	Electricity	RES-Wind	Wind on-shore	2018	1,500	30
Germany	Electricity	RES-Wind	Wind on-shore	2018	1,552	58

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