Global Gas Power Economics Model Methodology

October 2021

About Carbon Tracker

The Carbon Tracker Initiative is a team of financial specialists making climate risk real in today's capital markets. Our research to date on unburnable carbon and stranded assets has started a new debate on how to align the financial system in the transition to a low carbon economy.

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1 Overview

This document explains the methodology of our Global Gas Power Economics Model (GGPEM). GGPEM is a proprietary techno-economic simulation model which covers operating, under-construction and planned gas-fired capacity in the EU, UK and the US. Future iterations will expand the model globally. GGPEM provides unit or asset-level estimates of the:

- Capital cost, short-run marginal cost (SRMC) and long-run marginal cost (LRMC).
- Operating cashflow independent of cost and revenue hedging.
- Net Present Value (NPV) of new projects for select countries.
- Stranded asset risk in a below 2°C scenario.

2 Model inputs and definitions

2.1 Model inputs

To model the cost and cashflow profile of individual gas-fired power units it requires a comprehensive, detailed and diverse number of datasets. The GGPEM draws upon the most up-to-date data sources with regards to asset inventory data, asset performance data and technical, market and regulatory assumptions. This spans: pollution control technologies; recent unit capacity factors; fuel prices; and tariffs. National, regional or local policies governing environmental pollution, carbon prices, retirement schedules and market structures are also included.

The primary asset-level inventory data builds on the Global Energy Monitor (GEM) Global Gas Plant Tracker (GGPT) and Platts World Electric Power Plants (WEPP) databases[1]. The scope of the gas-power plants included in this study represent those plants that are in operation and those expected to be completed by end-2021. In addition, the units that are under construction and in planning stages have also been included. Plants that have an installed capacity of less than 20MW are excluded.

Table 1 – Universal Parameters in the Global Gas Economics Model

Parameter	Source	Details
Plant-level characteristics	GEM GGPT; National reports, statistics and databases.	Name; Location; Installed Capacity; Unit Status; Year of operation; Parent organisation; Sponsor organisation; Technology type; and Heat rate.
Cooling type and pollution control technologies by plant	Platts WEPP; National reports, statistics and databases; Consultancy reports.	Installed environmental control technologies for SO2; Cooling technology.
Fixed Operations & Maintenance (FOM) costs	IEA; National reports, statistics and databases; Consultancy reports.	Cost per kW. The fixed cost assumptions included in this report depend on the technology of the unit: combined cycle gas turbine, open cycle gas turbine and steam turbine. See 2.3.1.1
Non-fuel Variable Operations and Maintenance (VOM) costs	IEA; National reports, statistics and databases; Consultancy reports.	Cost per MWh. The variable costs we used depend on the technology of the unit: combined cycle gas turbine, open cycle gas turbine and steam turbine.
Capacity Factor	National reports, statistics and databases; Consultancy reports.	Granularity by asset or region in country, depending on country. Capacity yet to come online assumes a regional average.

[1] *For further information about the GGPT and WEPP see https://globalenergymonitor.org/projects/global-gas-plant-tracker/ and https://www.spglobal.com/platts/en/products-services/electric-power/world-electric-power-plants-database, respectively.*

Fuel cost	National statistics, reports; Country experts; Consultancy reports.	See 2.2.1.1
Carbon Price	ICAP, National reports, statistics and databases.	See 2.2.1.2
Combustion efficiency	IEA; Consultancy reports.	Low Heating Value (LHV).
Efficiency adjustments for cooling, age and pollution controls	EIA; IEA.	Adjustments made to the overall combustion efficiency of the plant.
Environmental control technology capital and operational costs	US EPA; National reports, statistics and databases; Consultancy reports.	Capex ($/kW), Fixed Operations and Maintenance ($/kw-yr) and Variable Operations and Maintenance ($/MWh). Adjusted for pollutant and nameplate capacity of plant.
Air pollution regulations	National and provincial regulations.	See 2.3.1.2
Plant revenues	National reports, statistics and databases; Consultancy reports.	Includes wholesale prices, regulated tariffs and various out-of-market revenues, where applicable.
Macroeconomic data	OECD; IMF; Bloomberg.	All values are represented in 2018 USD.
Country/Regional Grids	National reports, statistics and databases.	Dependent on whether an electricity grid in a country or region is administered by different system operators.
Unabated gas-fired power generation pathways	IEA's Beyond 2°C Scenario.	Specified for most countries, apportioned from region level where appropriate by share of existing gas capacity otherwise.
Levelised Cost of Energy	CTI analysis	The LCOE is the sum of all costs divided by the amount of generation. The costs include capital costs, capital recovery factor, FOM, VOM, fuel and carbon. See 2.4

2.2 Short Run Marginal Cost (SRMC)

We define the short-run marginal cost (SRMC) as the sum of fuel, carbon (where applicable) and variable operating & maintenance (VOM) costs.

2.2.1 Fuel cost

Calculating the delivery cost for gas at the unit level varies widely and depends on a number of criteria, the availability of domestic and imported gas in the country/region, the type of fuel gas used (regasified LNG or natural gas), the natural gas trading system (spot gas hubs or long-term LNG contract) and gas trading hubs of closest proximity (if any). The cost of gas can have a large impact to a gas-fired power plant's cost profile. Gas is transported in implicitly different ways depending on the form of gas product –natural gas is transported by pipeline within the local entry/exit system; while regasified liquified natural gas (LNG) must first be shipped to a local LNG terminal as a liquid before being regasified and transported to the power plant by pipeline. Furthermore, with the presence of long-term gas trading contracts with other countries, the Free on-board (FOB) price is different from gas spot price within the same region.

For the cost of gas we use the prices at the hub(s) of closest proximity, taken from Bloomberg LP and national statistics reports. For RLNG imported via long-term contracts, we calculate the FOB price at the LNG terminal by summing up the estimated contract price, shipping cost and regasification cost.

Figure 1 – Average fuel cost assumptions ($/MMBTU), detailed methodology at Section 7

Fuel cost assumptions ($/MMBTU)			
	Low	Average	High
EU	6.14	7.32	10.33
USA	1.35	3.02	12.02

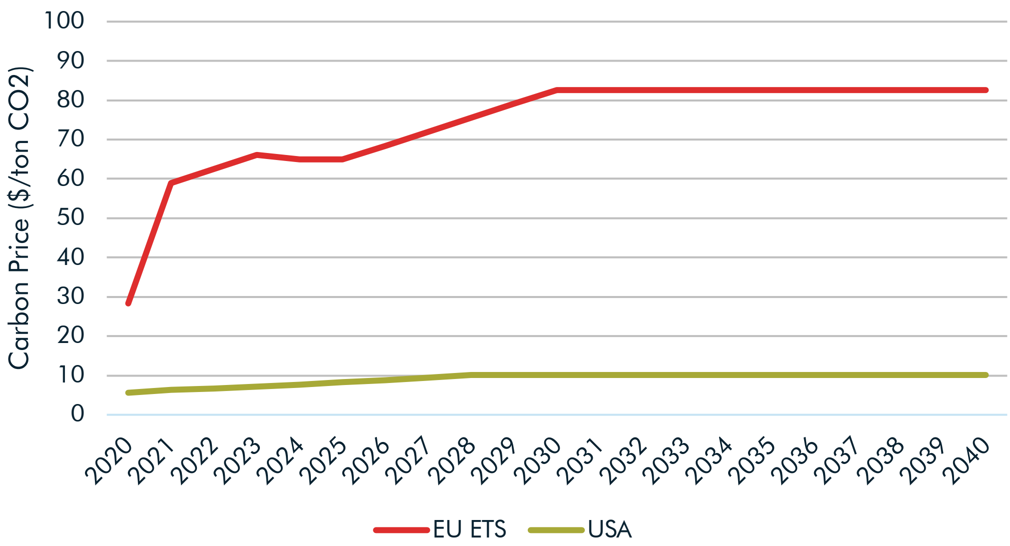
Source: Carbon Tracker Initiative (2021)

2.2.2 Carbon cost

We only include a carbon price where it is implemented or has been approved and will be implemented in the future. This includes the following markets:

- The European Union Emissions Trading System (EU ETS), our prices for which cover the EU27 member states, plus the UK. The UK ETS will be modelled in a future update.
- The Regional Greenhouse Gas Initiative which covers the states of Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, and Vermont.

Figure 2 – Carbon cost projections EU and USA ($/ton CO2)



Source: Carbon Tracker Initiative (2021)

2.2.3 Variable Operating & Maintenance (VOM) costs

VOM costs vary with the use of the unit. These costs include, but are not limited to, purchasing water, power and chemicals, lubricants and other supplies, as well as disposing of waste.

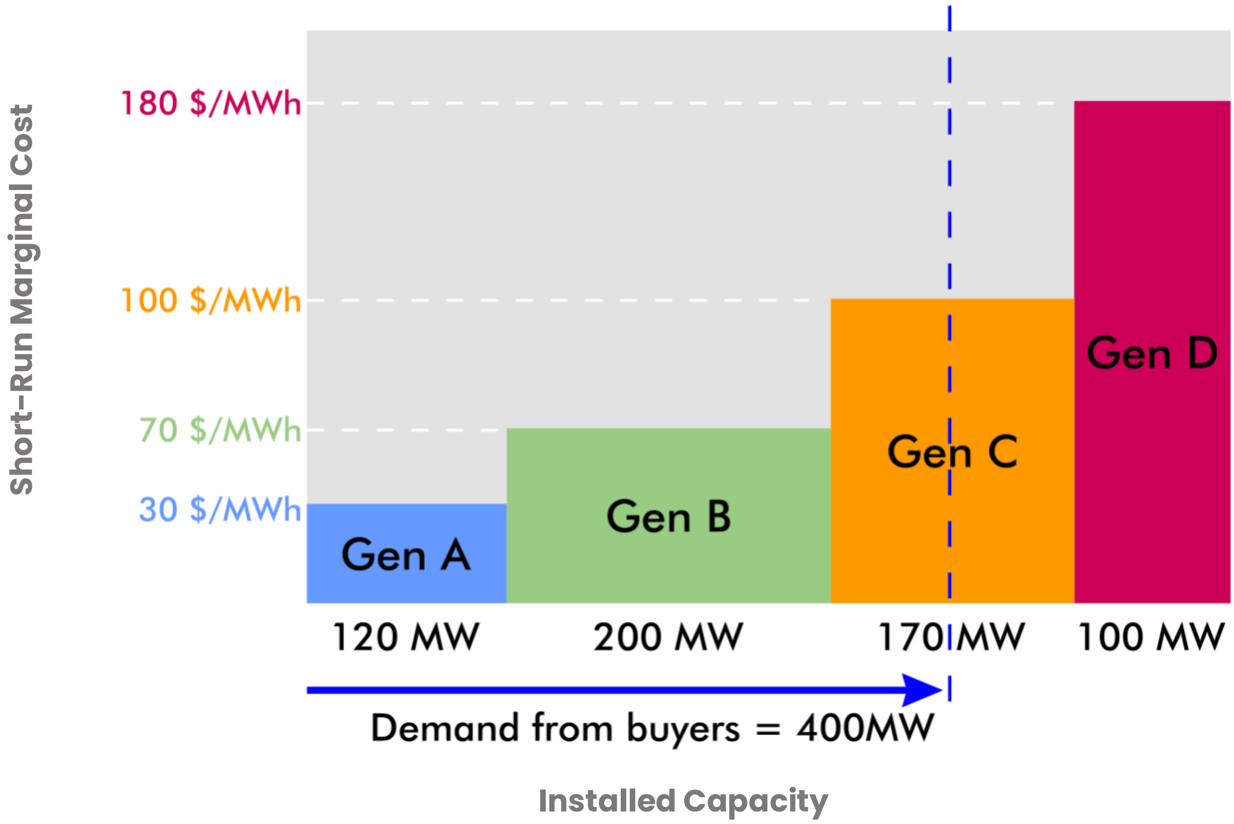
2.2.4 Short-run marginal cost (SRMC) and dispatch decisions

The SRMC cost tends to impact dispatch decisions in liberalised markets where units enter competitive markets for the right to sell power to consumers. In a simplified way, the liberalised markets operate in the following way:

- The grid operator forecasts power demand ahead of time.
- The grid operator asks for bids to supply quantity of power required to meet the forecast. Power generators typically bid at SRMC of producing the next unit of power.
- The grid operator starts purchasing the power offered by the lowest bid operators until they reach the required power in the forecast. This is called the uniform clearing price.
- The grid operator pays all suppliers the same uniform clearing price regardless of what they bid.

Figure 3 presents a stylised cost curve based on short-run operating cost.

Figure 3 – Merit order and dispatch decision



Source: Carbon Tracker Initiative (2021)

2.3 Long-run marginal cost (LRMC)

LRMC includes SRMC plus fixed operating and maintenance (FOM) costs and any capital additions from meeting environmental regulations. LRMC does not include the initial infrastructure cost in our definition.

2.3.1 Fixed operating & maintenance (FOM) costs

FOM include the expenses incurred at a power plant that do not vary significantly with generation and include staffing, equipment, administrative expenses, maintenance and operating fees. While the SRMC governs dispatch decisions, the LRMC impacts the bottom-line.

2.3.2 Air pollution regulations

There are a variety of policies and air quality standards designed to reduce air pollution across different regions and countries. For our analysis we principally focus on the NOx emission limits for existing gas-fired power plants, allowing us to understand which additional units will need to retrofit under existing environmental regulation. We only include environmental regulation where it is implemented or has been approved and will be implemented in the future. These regulations frequently change.

2.4 Operating cashflow

We calculate operating cashflow as the difference between the sum of all revenues and the LRMC. For the revenues structure we consider:

- in-market revenues which represent incomes from wholesale electricity markets based on peak and baseload prices
- out-of-market revenues representing payments from ancillary and balancing services
- capacity payments awarded with yearly auctions depending on the specific regulations in places in each country.

2.5 Levelized cost of energy (LCOE)

LCOE is a standard analytical tool used to compare power generation technologies and is widely used in power market analysis and modelling[2]. The LCOE is the sum of all the discounted costs divided by the discounted amount of estimated yearly electricity generation. The costs include capital costs, capital recovery factor, FOM, VOM, fuel and carbon. While the limitations of using LCOE analysis for understanding the economics of power generation have been well documented, this provides a simple proxy for when new investments in gas power no longer make economic sense and when investors and policymakers should plan and implement a gas power phase-out.

2.6 Below 2°C scenario retirement year

The year when the unit should be retired to be consistent with the temperature goal in the Paris Agreement. The retirement schedule is determined based on the long run marginal cost or operating cashflow.

2.7 Below 2°C scenario stranded asset risk

The potential operating cashflows lost from shutting the unit prematurely in accordance with the retirement year mentioned above.

2.8 Stranded asset

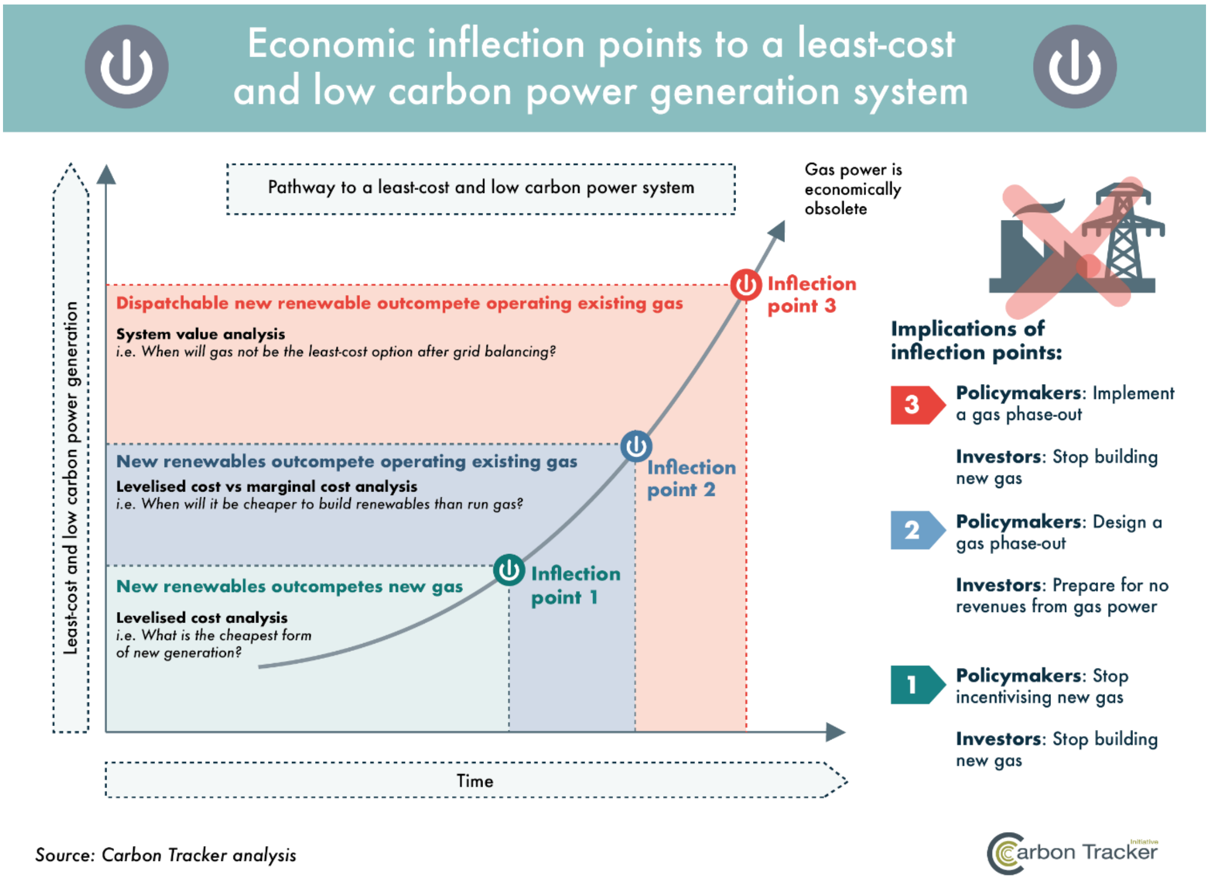
A fossil fuel energy and generation resources which, at some time prior to the end of their economic life (as assumed at the investment decision point), are no longer able to earn an economic return (i.e. meet the company's internal rate of return), as a result of changes in the market and regulatory environment associated with the transition to a low-carbon economy.

[2] *For more information refer to* https://www.nrel.gov/analysis/tech-lcoe-documentation.html

3 Stranded asset risk model

Our stranded asset risk model compares three tipping or inflection points that will make gas-fired power economically obsolete. There are three economic inflection points that policymakers and investors need to track to provide the least-cost power: when new renewables outcompete new gas; when new renewables outcompete operating existing gas; and when new firm (or dispatchable) renewables outcompete operating existing gas. These inflection points have implications for investors and policymakers, as detailed in Figure 4.

Figure 4. The intersection between the economic inflection points and the policymaking process for a least-cost power system



Source: Carbon Tracker analysis

Notes: We acknowledge that LCOE analysis is a limited metric as it does not consider revenues from generation and the system value of wind and solar. According to the IEA, the best way to integrate variable renewable energy (VRE) is to transform the overall power system through system-friendly deployment, improved operating strategies and investment in additional flexible resources. Flexible resources include better located generation, grid infrastructure, storage and demand side integration.3 See: IEA (2016), Next-generation wind and solar power: From cost to value.

[3] See: IEA (2016), Next-generation wind and solar power: From cost to value. See: https://www.iea.org/publications/freepublications/publication/NextGenerationWindandSolarPower.pdf

4 Below 2°C scenario model

Our below 2°C scenario model identifies the year when a gas unit needs to be retired and the amount of stranded asset risk associated with keeping the unit open. We define a stranded asset as the difference between the NPV of operating cashflows in a business as usual (BAU) scenario and a scenario consistent with the temperature goal in the Paris Agreement. The modelling approach involves three steps.

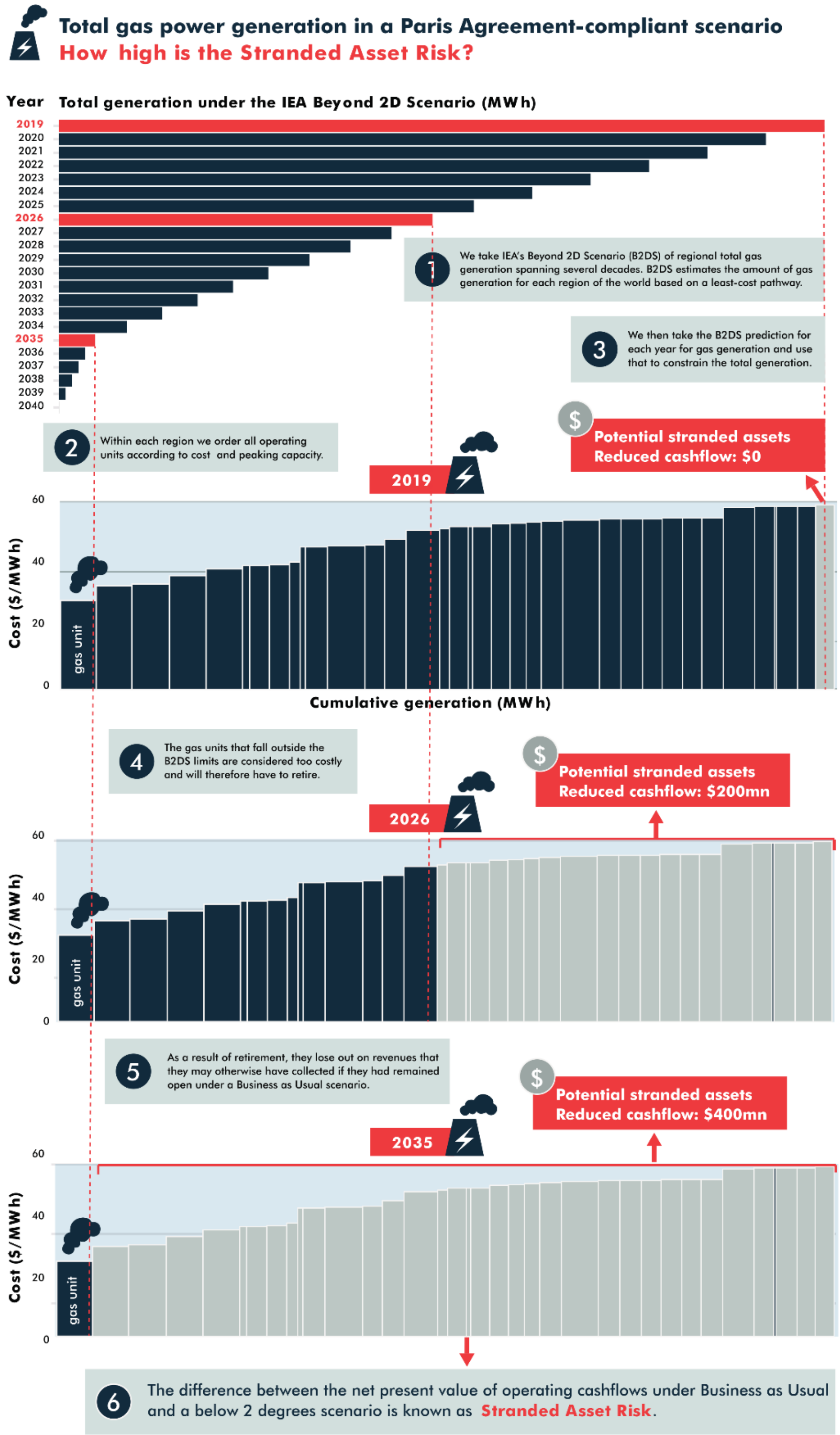
Firstly, we identify the amount of capacity that is required to fill the generation requirement in the IEA's beyond 2°C scenario (B2DS). Regions have different phase-out dates for gas generation, while in some cases, gas is not expected to be phased out. In the B2DS model, BECCS is expected to capture the emissions of operating gas plants. Because we recognise the limitations of this approach, we also model several other phaseout scenarios, including a net-zero by 2050 scenario, outlined in Section 4.1.

Secondly, we rank the gas-fired generation units to develop a retirement schedule, based on the authority, region or grid responsible for maintaining security of supply. The gas units are ranked according to the authority, region or grid responsible for maintaining security of supply and then ordered according to cost. Acknowledging that flexible gas turbine generation is necessary for fulfilling peak load electricity demand and other grid balancing services, units are also ranked by their turbine technology, capacity factor and operating cost (to determine their potential to become a peaking power plant (peaker). As a result, these phase-out schedules force high-cost, non-peaking generators to close first until the aggregated asset level generation reaches the limits set out in our chosen phaseout scenario.

Units with capacity factors greater than 25% were assumed to be baseload generation. Combined Cycle Gas Turbines (CCGTs) were assumed to be non-peakers, unless equipped with additional technologies, (e.g. a bypass stack). By comparing unabated gas-fired generation in our chosen phaseout scenario for each region, units with capacity factors greater than 25% which use CCGT technology are phased out first, followed by Steam Turbines (STs) and Open Cycle Gas Turbines (OCGTs), with capacity factor exceeding 25%. Using these factors, we identify the Paris -aligned retirement year for each unit.

Thirdly, we calculate the cash flow of every planned, operating and under-construction unit under our phaseout scenarios and a BAU scenario to understand stranded asset risk. Stranded asset risk is then defined as the difference between the NPV of operating cash flows in the BAU scenario (which includes announced retirements in company reports or otherwise assumes a lifetime of 50 years for steam turbines, and 30 years for other technologies; or 2025, whichever is later) and the NPV of operating cash flows in the chosen scenario. Figure 5 provides a schematic illustration of the below 2°C stranded asset modelling methodology.

Figure 5. Schematic illustration of the modelling methodology



Source: Carbon Tracker Initiative (2021)

4.1 Other Phaseout Scenarios

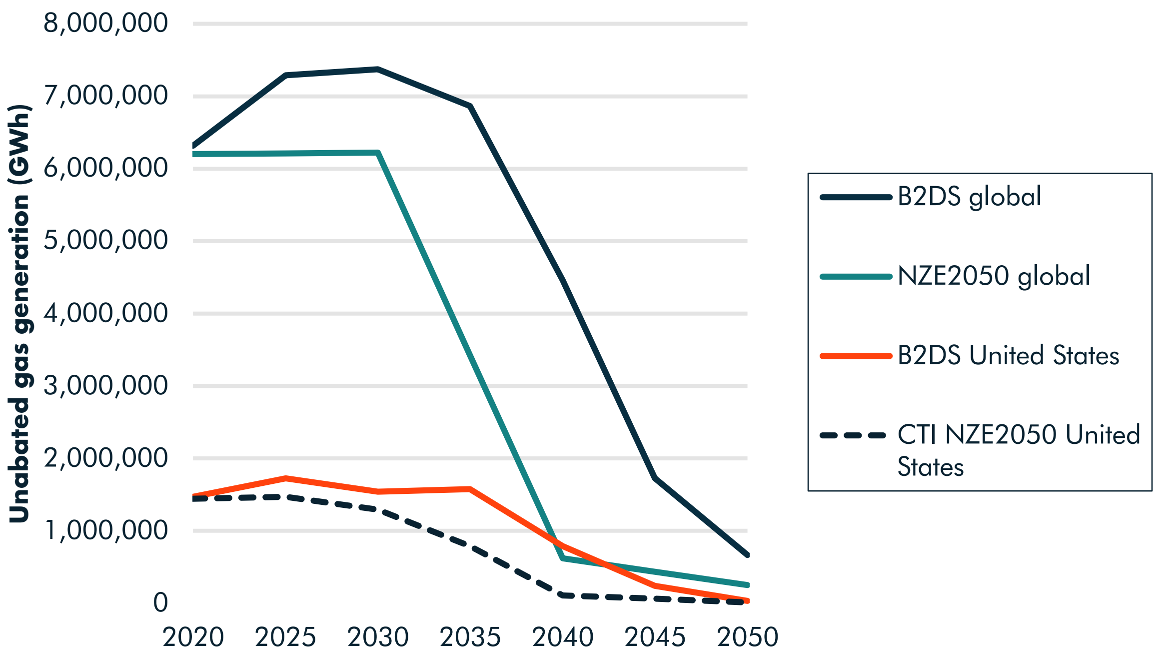
We adopt a similar methodology to the one presented above to calculate phaseout pathways and hence stranded asset risk under different scenarios.

In this report, in addition to the B2DS scenario we also model the following scenarios.

4.1.1 Carbon Tracker's Net Zero by 2050 scenario

The CTI net-zero by 2050 scenario is a regional interpolation of the IEA's global NZE2050 scenario and the B2DS. This is an interim scenario to model a net-zero 2050 phaseout of coal and gas while we await the release of a more granular scenario by the IEA. To estimate how coal and gas generation would decline under the more restrictive criteria of net-zero emissions by 2050, we scale each regional trajectory in the B2DS according to the ratio of the global NZE2050 to the global B2DS unabated coal and gas generation trajectories. This is illustrated by the graph below.

Figure 6. How we estimate a regional net-zero power generation trajectory



Source: Carbon Tracker Initiative (2021)

$$\textbf{Regional NZE2050 unabated gas generation}(region, year) = \frac{\text{Global NZE2050 unabated gas generation}(year)}{\text{Global B2DS unabated gas generation}(year)} \times \text{Regional B2DS unabated gas generation}(region, year)$$

We acknowledge that this interim scenario is not as rigorous as regional integrated assessment model. However, this is beyond the scope of our report and we will adopt regional IEA NZE2050 data when it becomes available.

4.1.2 Grid Lab 90% clean energy by 2035

We integrated GridLab's 90% clean energy by 2035 scenario[4] into our model as a proxy of Biden's 100% clean electricity by 2035 policy proposal. We also added an additional step to phase out all gas generation by 2040. A key advantage of the GridLab scenario is the RTO-level granularity of the data. This allows us to estimate phaseout dates for gas power plants which are unconstrained by technical requirements.

[4] *See* https://www.2035report.com/electricity *for further details.*

5 Project Finance

Project finance modelling assesses the risk-reward of lending to, or investing in, a gas power project and includes a forecast of revenues, capital expenditures, operating and maintenance costs, taxes, interest expenses and debt instalments. These forecasts are used to produce after-tax cashflows which are used to calculate the Net Present Value (NPV) for each project.

In selected countries we calculate the economics of al new gas plants that, according to GEM's database, are either at under construction or proposed status. We exclude CHP plants as their profitability depends highly on the remunerations relative to the cogeneration service and this falls outside the scope of our report. For every selected country in the project finance module, we integrate GEM database with an in-house analysis to ensure that all the plants we are considering are being developed and that we are not overseeing any major project. Our additional analysis looks at company reports, official decisions from environmental permitting agencies, company statements and news reports.

For each unit analysed in the project finance model we calculated the investment cost and the split between private equity and loan based on data internally sources, see Section 5.2. The project finance model uses revenues (total operating revenues) and costs (long run marginal cost) calculated in the Global Gas Power Economics Model (GGPEM) to estimate yearly EBITDA. In addition, we consider depreciation, loan repayments (based on outstanding debt and interest) and taxes to calculate yearly cashflows. Subsequently, using yearly cashflows and our WACC estimates we can calculate the yearly NPV of the project and other financial indicators such as Debt Service Cover Ration and EBITDA margin. The NPV is the defined as the discounted sum of all the investment costs and cashflows incurred during the lifetime of a project.

Project finance results are calculated for all the different phaseout scenarios considered in the model.

The project finance model analyses gas units in Belgium, Greece, Italy, Poland, Romania, the UK and the US.

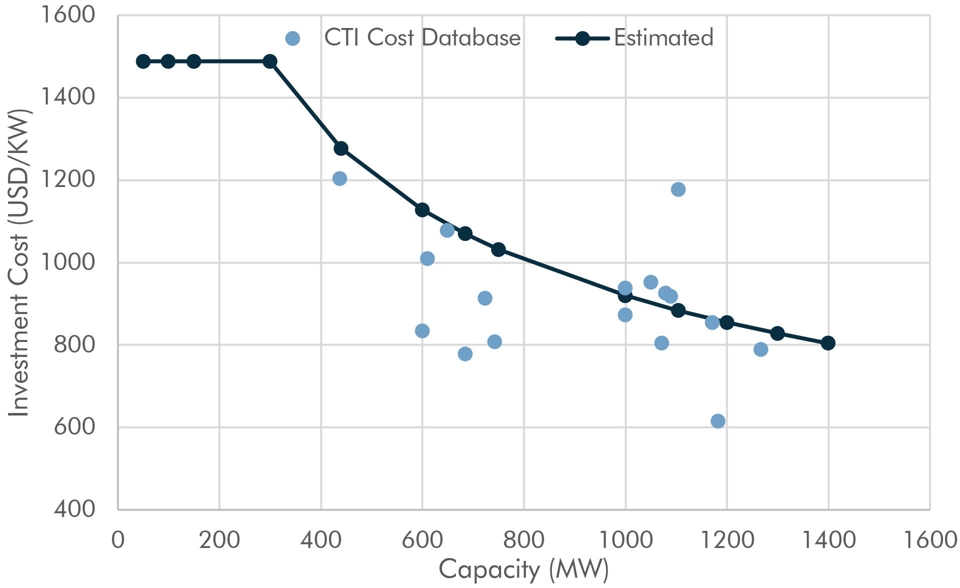
5.1 Investment cost estimates

We calculated the investment cost of new projects using a formula that considers economy of scale based on the size of the project:

$$\text{Investment costs (\$/kW)} = \text{Reference cost (\$/kW)} \times \left(\frac{\text{Reference capacity (MW)}}{\text{Installed capacity (MW)}}\right) \times \text{scale factor}$$

Reference cost and reference capacity has been selected for each country based on a database of costs for new projects based on an internal analysis of multiple sources. The scale factor has been selected with an empirical process in order to represent well the distribution of costs found in our database. For CCGTs, we selected a cut-off for plants smaller than 300 MW in order to avoid over estimating costs for small plants. A comparison a sample of cost data for projects under development and our estimates for US is shown in the graph below.

Figure 7. US comparison of investment costs estimated vs CTI cost database



Source: Carbon Tracker Initiative (2021)

5.2 Project Finance Assumptions EU and USA

PARAMETER	DETAIL	SOURCE
Investment Cost (US$/kW)	Investment cost has been calculated following the methodology presented in Section 5.1. For CCGTs in US, Italy, Greece and Romania we base our estimates based on the reported costs of a sample of the projects under development. We collected investment data at plant level from a multitude of sources such as newspaper articles, companies statements, annual reports, third-party analysis and press releases. For UK we use official government sources (BEIS 2020) while for Belgium and Poland we use averages of the other countries. For OCGTs in Europe we use estimates from (BEIS 2020) while for US we use in-hose estimates based on an inventory of costs of projects under development.	*Carbon Tracker estimates* *BEIS (2020)*
Weighted Average Cost of Capital (WACC) (%)	Our WACC estimates are based on a database of financial indicators for power utilities developing new gas-fired plants in EU and US from Bloomberg terminal (updated on Q2 2021). We calculated country-specific values using the average values of the public listed utilities developing new projects in that country. Due to lack of data, for Romania we used the average values of the other EU countries. We did not calculate a project specific WACC because in many cases such granular data was not available or was extremely limited.	*Bloomberg terminal* *Carbon Tracker estimates*
Debt and Equity Ratio (%)	We calculated country-based split of equity and loan following the same method used for WACC (See above)	*Bloomberg terminal* *Carbon Tracker estimates*
Interest rate (%)	We calculated country-based estimates of interest rate based on the cost of debt of	*Bloomberg terminal* *Carbon Tracker estimates*

	companies following the same method used for WACC (See above)	
Construction period (years)	Construction periods are assumed to be 3 years for CCGTs and 2 years for OCGTs	*Carbon Tracker estimates*
Useful life of plants (years)	We assume gas plants would have a useful economic life of 30 years. We assume straight line deprecation over the same period to reflect this.	*Carbon Tracker estimates*
Debt financing term and Interest rate (%)	We assume a debt financing period of 20 years.	*Carbon Tracker estimates*
Tax rate (%)	Corporate tax rates are estimated at the country-level and taken from KPMG.	*KPMG (2021)*

6 Risks and limitations

While the modelling and analysis aims to utilise the most up-to-date and detailed data, there are a number of limitations given the comprehensive nature of the study. The principal limitations/caveats include:

- Many parameters and assumptions are subject to constant change. This includes a variety of policy, economic and technological assumptions. As a result, the assumptions will be updated on a periodic basis.
- Gas is traded and contracted in multiple ways, with supply contracts often not publicly available. We use spot prices for international trade using price indices from Bloomberg.
- If a plant is assumed to be required to install an environmental control technology, we do not factor in the reduction to the plant's utilisation.
- Gas-fired power plants can derive revenues through multiple grid services they provide. This is dependent from grid to grid, however, can include wholesale pricing, capacity payments, regulated tariffs to name a few. This can also be traded over different periods. We aim to reflect this as accurately as possible using publicly available data and through conversations with local experts, however data provision or granularity can prohibit this in certain regions (such as visibility of power purchase agreements (PPAs)).
- The methodology used assumes that markets are efficient, and that the projects with the lowest supply costs are used to satisfy demand on an aggregate basis over a period. Given the highly regulated nature of power markets, the cyclical nature of commodity markets and other factors that influence electricity prices, this may not be what is realised in reality.
- We only include environmental regulation and carbon pricing where it is implemented or has been approved and will be implemented in the future. These regulations frequently change.
- Besides carbon prices, we do not forecast commodity prices and use 1-3-year averages for our forward-looking estimates. In addition, we assume a continuation of plants based on 2018 statistics. We do not try and model the impact to gas from a system perspective, nor attempt to model the change to a plant's generation over time.
- We assume that gas-fired power will need to be phased out and do not make any explicit assumptions on the retrofitting of CCS to existing capacity. This is however incorporated in the IEA B2DS, upon which our climate scenario modelling is derived.
- Future costs do not take into consideration decommissioning, retirement or clean-up costs when they are phased out. Nor do we make assumptions on the technical lifetimes of gas plants.
- We do not adjust efficiency for atmospheric condition to gas plants. Instead thermal efficiencies of the plants are assumed by technology, age and adjustments from additional environmental control or cooling technologies.
- Several plants captured in the inventory data produce heat as well as electricity (Combined Heat and Power – CHP). We do not factor in the revenues derived from heat production and only capture the value delivered in the form of electricity.
- Captive plants, typically tied to a large industrial site, are treated in a similar fashion to all gas plants on the grid and will be phased out accordingly.
- No revenue and cost hedging are assumed. Utilities often hedge their revenue and cost exposure through the future and forward markets. The level and extent of hedging varies depending on whether the utility operates in a liberalised or regulated market, as well as the evolution of power market price formation.
- Estimating FOM is challenging. The amount an operator spends on FOM depends on a variety of factors, such as the useful life of the unit, air pollution regulations and long-term fuel contracts.

7 Regional assumptions

7.1 European Union

7.1.1 Gas model assumptions

PARAMETER	DETAIL	SOURCE
Inventory data on unit-level characteristics	Unit name, plant name, plant location, unit installed capacity; unit status, year of unit operation, parent organization, technology type, heat rate, and emissions factor.	Global Energy Monitor (2021) Carbon Tracker estimate
Cooling type and pollution control technologies by plant	Installed environmental control technologies for nitrogen dioxide, as well as the type of cooling technology.	Platts (2020)
FOM	Fixed O&M assumptions depend on the technology of the boiler: US$10.52/kW for OCGT; US$13.15/kW for CCGT; US$11.20/kW for ST. Costs are inflation adjusted. The values for OCGT and CCGT are obtained from the report by Department of Energy and Climate Change and Leigh Fisher (2016), while that for ST is calculated from the O&M costs estimated by IEA WEO (2015), assuming a mid point of 25% to 75% of total O&M costs being FOM - as suggested by Leigh Fisher (2016)	Carbon Tracker estimates based on *IEA (2015)* *Department of Energy and Climate Change and Leigh Fisher (2016)*
VOM	Variable O&M assumptions depend on the technology of the boiler: US$1.18/MWh for OCGT; US$1.91/MWh for CCGT; US$1.09/MWh for ST. Costs are inflation adjusted. The values for OCGT and CCGT Department of Energy and Climate Change and Leigh Fisher (2016), while that for ST is from EPA's documentation for EPA Platform (2018).	*Department of Energy and Climate Change and Leigh Fisher (2016)* *EPA (2018b)*
Fuel quality	Gas quality, expressed in terms of energy content (MJ/m3), is obtained at a country level from data by European Union (2018). We take an average of the maximum and minimum Gross Calorific Value (GCV) for 2nd Family gas for each country.	*European Union (2018)*
Capacity factor	Obtained at asset-level for 2017-2020. For 2021 onwards we use the average from the previous years. Any remaining missing values were filled using country averages. Values were clipped at a minimum of 1% and a maximum of 90% to avoid data inconsistencies.	ENTSO-E (2021)
Fuel cost	Fuel costs include only the expenses incurred in buying natural gas. Due to unavailability of data, we assume natural gas price for each country using the annual average of hub price(s), among all available data from Bloomberg, closest to each country as a proxy. Gas transmission tariff is assumed negligible, which we agree to be reasonable as, for example, taking the transmission tariff figure from ACER's report, UK-Germany average cross-border pipeline entry/exit tariff was merely 2% of the average gas price in 2019.	*Bloomberg (2020)* Carbon Tracker estimate *ACER (2018)*
Carbon price	Historic EU ETS prices for past years, assuming €33 for 2021, €35 by 2024 and steadily rising to €70 by 2030. We do not consider hedging of allowances which may account for lower or higher prices at utility level.	Carbon Tracker estimate
Combustion efficiency	Gross, low heating value (LHV) adjusted for unit age. Baseline values are boiler type specific: 42% for OCGT, 60% for CCGT (from Ricardo-AEA, 2012) and 35% for ST (from EIA, 2018). The value for each modelled year is adjusted by an annual factor of 0.46%, commencing from the start year of the unit, as indicated in GE Power Systems' report (2000).	*Ricardo (2015)* *EIA (2018)* *GE Power Systems (2000)*
Efficiency adjustments from cooling and pollution controls	Adjustments made to the overall combustion efficiency of the plant depending on the technology installed.	EPA (2018)
Environmental control technology capital and operational costs	These costs include fixed operations and maintenance ($/kW per year) and variable operations and maintenance ($/MWh). Adjusted for pollutant and nameplate capacity of plant.	EPA (2018)
Unabated gas-fired power generation pathway for below 2°C scenario	We take the IEA B2DS projections for gas generation within the European Union.	IEA (2017) Carbon Tracker estimate
Pollution limit regulations and associated capital	The Industrial Emissions Directive and BREF regulations give emissions rates per pollutant. We assume that in 2021, all units that fail BREF regulations will need new control technology for Nitrous Oxide (NOx).	European Commission EEB (2016)

and operational costs		
Plant revenues	Calculated from country-level power tariffs for baseload and peakload from Bloomberg, filled with day ahead prices from ENTSO-E. Out-of-market payments are included where appropriate. Balancing and ancillary services payments were assumed constant across the fleet. Capacity payment revenues are included for Belgium, France, Ireland, Italy, Poland and the UK. For the UK data is from Ember (formerly Sandbag) and for Poland from PSE, disaggregated to unit-level through own estimates, and cross-checked with Instrat data.	*Bloomberg (2021)* ENTSO-E (2021) *Sandbag (2017)* *PSE (2018, 2019, 2020)* Instrat (2021)

7.1.2 Renewable LCOE assumptions

Germany

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind		
Capital Expenditure	CAPEX data together with cost breakdown was sourced from IRENA 2018 cost report. A lower and upper band was calculated using a 20% assumption.	IRENA (2019)
O&M Costs	O&M cost data was assumed to be 2% of CAPEX and was sourced from IEA research. A lower and upper band was calculated using a 20% assumption.	IEA Wind (2019)
Capacity factor	Country level capacity factor data was sourced from IRENA 2018 cost report. A lower and upper band was calculated using a 20% assumption. Local capacity factors were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019)
Return on Equity	Return on equity was estimated using the median between data for Europe from NYU Stern.	*NYU* Stern (2019)
Cost of Debt	Data on lending rates from World Bank was not available for Germany and was sourced from a combination of OECD data and a commercial data provider. 1% was added to account for long term risks. Inflation data was sourced from IMF.	OECD (2019) Market Inspector (2019) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from the REMAP dataset for G20 countries. A learning rate of 30% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2019a)
Assumptions for solar PV		
Capital Expenditure	CAPEX data together with cost breakdown was sourced from IRENA 2018 cost report. A lower and upper band was calculated using a 20% assumption.	IRENA (2019)
O&M Costs	O&M cost data was assumed to be 1.2% of CAPEX and was sourced from a US study from NREL and slightly increased for Germany.	NREL (2017) New Energy Update (2019)
Capacity factor	Country level capacity factors were assumed to be slightly higher than the ones observed in Poland. A lower and upper band was calculated using a 20% assumption. Local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis	Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using the median between data for Europe from NYU Stern.	*NYU* Stern (2019)
Cost of Debt	Data on lending rates from World Bank was not available for Germany and was sourced from a combination of OECD data and a commercial data provider. 1% was added to account for long term risks. Inflation data was sourced from IMF.	OECD (2019) Market Inspector (2019) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from the REMAP dataset for G20 countries. A learning rate of 37% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2019a)

United Kingdom

Parameter	detail	Source
Assumptions for onshore wind		
Capital Expenditure	CAPEX data together with cost breakdown was sourced from IRENA 2018 cost report. A lower and upper band was calculated using a 20% assumption.	IRENA (2019)
O&M Costs	O&M cost data was assumed to be 2% of CAPEX and was sourced from IEA research on Germany and maintained for United Kingdom. A lower and upper band was calculated using a 20% assumption.	IEA Wind (2019) *IEA Wind (2019a)*
Capacity factor	Country level capacity factor data was sourced from the same IRENA report. A lower and upper band was calculated using a 20% assumption. Local capacity factors were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019)
Return on Equity	Return on equity was estimated using the median between data for Europe from NYU Stern. The rate was the same as In the case of Germany.	*NYU Stern (2019)*
Cost of debt	Data on lending rates from World Bank was not available for United Kingdom and was sourced from a combination of OECD data and a commercial data provider. 2% were added to account for long term risks. Inflation data was sourced from IMF.	OECD (2019) Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from the REMAP dataset for G20 countries. A learning rate of 35% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2019a)
Assumptions for solar PV		
Capital Expenditure	CAPEX data together with cost breakdown was sourced from IRENA 2018 cost report. A lower and upper band was calculated using a 20% assumption.	IRENA (2019)
O&M Costs	O&M cost data was assumed to be 1.0% of CAPEX and was sourced from a US study from NREL.	NREL (2017) NREL (2018)
Capacity factor	Capacity factor was sourced from a real world project, from the developer's website. A lower and upper band was calculated using a 20% assumption. Local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	Hive Energy (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using the median between data for Europe from NYU Stern. The rate was the same as In the case of Germany.	*NYU Stern (2019)*
Cost of Debt	Data on lending rates from World Bank was not available for United Kingdom and was sourced from a combination of OECD data and a commercial data provider. 2% were added to account for long term risks. Inflation data was sourced from IMF.	OECD (2019) Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from the REMAP dataset for G20 countries. A learning rate of 28% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2019a)

Poland

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind		
Capital Expenditure	CAPEX data for Poland was sourced from real world project data from a set of projects that won fixed tariffs in a 2018 auction. CAPEX break down was sourced from an IRENA publication on costs. A lower and upper band was calculated using a 20% assumption.	IRENA (2019) *EBRD (2018)* *EBRD (2019)*
O&M Costs	O&M costs were assumed to be 1.75% of CAPEX per year. Lower and upper bands were calculated using a 20% assumption.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were assumed to be 0.33 and were sourced from real world project data (the same batch as the ones used for CAPEX data). Lower and upper bands were calculated using a 20% assumption. Local capacity factors were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm.	IRENA (2019) *EBRD (2018)* *EBRD (2019)* Protected Planet (2019) ESA (2019) Global Wind Atlas (2019)

Return on Equity	Return on equity was assumed to be 12.45% and was sourced from CSI market, to which 3% was added to be more in line with regional expected returns on equity.	CSI Market (2019)
Cost of Debt	Data on long term lending rates was sourced from CEIC and 2% was added. World Bank and NYU Stern do not have specific data for Poland. Inflation data was sourced from IMF. A lower and upper band was calculated using a 20% assumption.	CEIC (2019) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from a REMAP study for Poland. A learning rate of 17% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2015)
Assumptions for solar PV		
Capital Expenditure	CAPEX data was sourced from real world projects and from discussions with personal contacts working on engineering and construction projects in Poland. CAPEX breakdown was sourced from IRENA. A lower and upper band was calculated using a 20% assumption.	PV Magazine (2019)
O&M Costs	O&M costs were assumed to be 1.65% of CAPEX. A lower and upper band was calculated using a 20% assumption.	Carbon Tracker Estimate
Capacity factor	Capacity factor data was sourced from real world projects developed in Poland and quoted for CAPEX data. A lower and upper band was calculated using a 20% assumption. Local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	PV Magazine (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was assumed to be 12.45% and was sourced from CSI market, to which 3% was added to be more in line with regional expected returns on equity.	CSI Market (2019)
Cost of Debt	Data on long term lending rates was sourced from CEIC to which 2% was added. World Bank and Damodaran do not have specific data for Poland. Inflation data was sourced from IMF. A lower and upper band was calculated using a 20% assumption.	CEIC (2019) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from a REMAP study for Poland. A learning rate of 19% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2015)

Italy

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind		
Capital Expenditure	CAPEX data together with cost breakdown was sourced from IRENA 2018 cost report. A lower and upper band was calculated using a 20% assumption.	IRENA (2019)
O&M Costs	O&M cost data was assumed to be 2% of CAPEX and was sourced from IEA research on Germany and maintained for Italy. A lower and upper band was calculated using a 20% assumption.	IEA Wind (2019) IEA Wind (2019a)
Capacity factor	Country level capacity factor data was sourced from IRENA 2018 cost report. A lower and upper band was calculated using a 20% assumption. Local capacity factors were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019)
Return on Equity	Return on equity was estimated using the median between data for Europe from NYU Stern. The rate was the same as in the case of Germany.	NYU Stern (2019)
Cost of Debt	Data on lending rates was sourced from World Bank to which 2% was added to account for long term risks. Inflation data was sourced from IMF.	World Bank (2018) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from the REMAP dataset for G20 countries. A learning rate of 30% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2019a)
Assumptions for solar PV		
Capital Expenditure	CAPEX data together with cost breakdown was sourced from IRENA 2018 cost report. A lower and upper band was calculated using a 20% assumption.	IRENA (2019)
O&M Costs	O&M cost data was assumed to be 1.2% of CAPEX and was sourced from a US study from NREL, slightly increased for Italy.	NREL (2017) NREL (2018)
Capacity factor	Capacity factor was assumed to be 18% to account for more solar resources in Southern Europe. A lower and upper band was calculated using a 20% assumption. Local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraints not captured by the local analysis.	Global Solar Atlas (2019) Carbon Tracker estimate

Return on Equity	Return on equity was estimated using the median between data for Europe from NYU Stern. The rate was the same as in the case of Germany.	NYU Stern (2019)
Cost of Debt	Data on lending rates was sourced from the World Bank to which 2% was added to account for long term risks. Inflation data was sourced from the IMF.	World Bank (2018) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from the REMAP dataset for G20 countries. A learning rate of 30% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2019a)

Spain

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for both technologies was sourced from IRENA 2018 cost report.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors for both wind and solar were sourced from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxy data from neighbouring countries. Inflation data was sourced from IMF.	IMF (2019)
Cost of Debt	Data on lending rates was sourced from a financial statistics website (Trading Economics) as the World Bank did not have data available for Spain.	Trading Economics (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced using ration observed among countries modelled by the REMAP team at IRENA and additional data from research pieces and solar Power Europe. A high learning rate of 32% was used for onshore wind and a mid-value of 19% was used for solar PV.	*Solar Power Europe (2019)* *RED* (2018) IRENA (2019a)

Romania

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for both technologies was sourced through local experts and discussion with engineering companies active in the market.	Local experts
O&M Costs	O&M costs were assumed to be 2.2% of CAPEX for wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was sourced from local sources active in the market.	Local experts
Cost of Debt	Data on lending rates was sourced from World Bank to which 1.5% was added to account for long term risks associated to project financing. Inflation data was sourced from IMF.	World Bank (2018) IMF (2019)
Capacity deployment and learning rate	Deployment projections were made using rates of growth observed in countries modelled by the REMAP team at IRENA. A mid-level learning rate of 24% was used for onshore wind and 15% for solar PV.	IRENA (2019a)

Bulgaria

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Bulgaria was sourced from a triangulation of IRENA costs data and data on Romania, as a neighbouring country with similar conditions.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.5% for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraints not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was assumed to be slightly higher than Romania's.	Carbon Tracker estimate
Cost of Debt	Data on lending rates was sourced from World Bank. Inflation data was sourced from IMF.	World Bank (2018) IMF (2019)
Capacity deployment and learning rate	Capacity projections were estimated using growth rates observed in REMAP research. A learning rate of 21% (mid) was used for onshore wind while a learning rate of 25% (mid) was used for solar PV.	IRENA (2019a)

France

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for France for both technologies was sourced from IRENA report on costs in 2018.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.3% for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was assumed to be 8.5% in line with assumptions used for neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Data on lending rates was sourced from Trading Economics and upped by 1% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections were sourced from REMAP datafile as France is a G20 member. A learning rate of 22% was used for onshore wind (mid) and 20% for solar PV (mid).	IRENA (2019a)

Portugal

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Portugal for both technologies was estimating using IRENA cost data and neighbouring countries estimates, mainly Spain.	IRENA (2019)
O&M Costs	O&M was assumed to be 2.1% of CAPEX for onshore wind and 1.4% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report.	IRENA (2019) Protected Planet (2019)

	Local capacity factors were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was assumed to be 10% based on neighbouring countries proxies.	Carbon Tracker estimate
Cost of Debt	Data on lending rates was sourced from Trading Economics and increased by 1% to account for long term risks. Inflation data was sourced from IMF.	World Bank (2018) IMF (2019)
Capacity deployment and learning rate	Long term projections of deployment were made using observed rates of growth in REMAP research. A learning rate of 39% was assumed for onshore wind (high) and 20% for solar PV (mid).	IRENA (2019a)

Greece

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Greece for both technologies was estimated using IRENA costs data and proxies from Southern European economies.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2.2% of CAPEX and 1.5% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was assumed to be 13% in line with higher expected returns for Southern European economies.	Carbon Tracker estimate
Cost of Debt	Data on lending rates was sourced from Trading Economics and increased by 1.5% to account for long term risks. Inflation data was sourced from IMF.	World Bank (2018) IMF (2019)
Capacity deployment and learning rate	Long term projections of deployment were estimated using growth rates observed in REMAP research. A learning rate of 35% (high) was used for onshore wind and 28% (mid) for solar PV.	IRENA (2019a)

Sweden

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for onshore wind and solar PV in Sweden was sourced and estimated using IRENA (2019) cost data and IEA research.	IRENA (2019) *IEA Wind (2017)*
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate

Cost of Debt	Lending rates were sourced from Trading Economics and increased by 2.5% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 18% (mid) was used for onshore wind and 19% (mid) for solar PV.	IRENA (2019a)

Ireland

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Ireland for onshore wind and solar PV was estimated using IRENA data for 2018 and neighbouring country data.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics and increased by 2.5% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 16% (mid) was used for onshore wind and 11% (mid) for solar PV.	IRENA (2019a)

Netherlands

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for onshore wind and solar PV for Netherlands was estimated using IRENA (2019) data and neighbouring countries proxies.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics and increased by 1% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 14% (mid) was used for onshore wind and 21% (mid) for solar PV.	IRENA (2019a)

Finland

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Finland for onshore wind and solar PV was estimated using IRENA (2019) data.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics and increased by 0.25% to account for long term risks.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 16% (mid) was used for onshore wind and 19% (mid) for solar PV.	IRENA (2019a)

Denmark

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Denmark for onshore wind and solar PV was estimated using IRENA (2019) data	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors for wind were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics. Inflation data was sourced from IMF	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 17% (mid) was used for onshore wind and 25% (high) for solar PV.	IRENA (2019a)

Hungary

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Hungary for onshore wind and solar PV was estimated using IRENA (2019) data and neighbouring country proxies.	IRENA (2019)

O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics increased by 3% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 14% (mid) was used for onshore wind and 27% (high) for solar PV.	IRENA (2019a)

Austria

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Austria for onshore wind and solar PV was estimated using IRENA (2019) data and neighbouring country proxies.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics and increased by 1.5% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 17% (mid) was used for onshore wind and 23% (high) for solar PV.	IRENA (2019a)

Czech Republic

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Czech Republic for onshore wind and solar PV was estimated using IRENA (2019) data and neighbouring country proxies.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate

Cost of Debt	Lending rates were sourced from Trading Economics and increased by 1.2% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 22% (high) was used for onshore wind and 23% (high) for solar PV.	IRENA (2019a)

Croatia

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Croatia for onshore wind and solar PV was estimated using IRENA (2019) data and neighbouring country proxies.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics and increased by 1.5% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 25% (high) was used for onshore wind and 12% (high) for solar PV.	IRENA (2019a)

Slovakia

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Slovakia for onshore wind and solar PV was estimated using IRENA (2019) data and neighbouring country proxies.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics and increased by 1.5% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 8% (low) was used for onshore wind and 21% (mid) for solar PV.	IRENA (2019a)

Slovenia

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind & solar PV		
Capital Expenditure	CAPEX data for Slovenia for onshore wind and solar PV was estimated using IRENA (2019) data and neighbouring country proxies.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 2% of CAPEX for onshore wind and 1.2% of CAPEX for solar PV.	Carbon Tracker estimate
Capacity factor	Country level capacity factors were obtained from IRENA 2018 cost report. Local capacity factors for wind were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm. For solar, local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was estimated using proxies from neighbouring countries.	Carbon Tracker estimate
Cost of Debt	Lending rates were sourced from Trading Economics and increased by 1.5% to account for long term risks. Inflation data was sourced from IMF.	Trading Economics (2019) IMF (2019)
Capacity deployment and learning rate	Long term projections of capacity deployment were estimated using growth rates from REMAP research. A learning rate of 9% (low) was used for onshore wind and 19% (mid) for solar PV.	IRENA (2019a)

7.2 United States

7.2.1 Gas model assumptions

PARAMETER	DETAIL	SOURCE
Inventory data on unit-level characteristics	Unit name, plant name, plant location, unit installed capacity; unit status, year of unit operation, parent organization, technology type, heat rate, and emissions factor.	*Global Energy Monitor (2021)* EPA (2016) Catalyst Cooperative (2021) based on EIA (2020), FERC (2020)
Cooling type and pollution control technologies by plant	Installed environmental control technologies for nitrogen dioxide.	*Platts (2020)*
FOM	Unit-level FOM costs are extracted from EIA data via PUDL, for 20017-2019 and the average from those years for 2020 onwards. For units without this data, we fill in missing data depending on the combustion technology of the boiler. We assume US$9/kW for OCGT technologies; US$15/kW for CCGT technologies; US$12/kW for ST technologies. The values for OCGT and CCGT are obtained from the report by Department of Energy and Climate Change and Leigh Fisher (2016), while that for ST is calculated from the O&M costs estimated by IEA WEO (2018), assuming FOM as the half of total O&M costs - as suggested by Leigh Fisher (2016)	Catalyst Cooperative (2021) based on EIA (2020), FERC (2020) Carbon Tracker estimates based on *IEA (2018)* *Department of Energy and Climate Change and Leigh Fisher (2016)*
VOM	Unit-level VOM costs are extracted from EIA data via PUDL. For units without this data, we fill in missing data depending on the combustion technology of the boiler. We US$3.5/MWh for OCGT; US$3.5/MWh for CCGT; US$2.0/MWh for ST. Costs are corrected by inflation. The values for OCGT and CCGT Department of Energy and Climate Change and Leigh Fisher (2016), while that for ST is from assuming 57% CCGT value (CTI estimate).	Catalyst Cooperative (2021) based on EIA (2020), FERC (2020) *Department of Energy and Climate Change and Leigh Fisher (2016)* Carbon Tracker estimate
Fuel quality	Gas quality, expressed in terms of energy content (MJ/m3), is a CTI estimate of 39.9 (MJ/m3) motivated by European Union (20181) and EIA data.	*European Union (2018)* *EIA (2020)*
Capacity factor	Unit and Plant-level capacity factors are extracted from EIA data via PUDL for 2017-2019 and at Plant-level directly from EIA for 2020. For every year after this we project forwards using the average from 2018-2019, assuming a 2% year-on-year decline.	Catalyst Cooperative (2021) based on EIA (2020), FERC (2020) *EIA (2019, 2020)*

	If there are any missing capacity factors, we fill gaps first by unit state-technology average, or by plant. If not possible then we use the percentage change in the state technology average from one year to the next.	Carbon tracker estimate
Fuel cost	Yearly plant-level cost and state-level cost from EIA data via PUDL. EIA publishes a natural gas electric power price, which is the average of the natural gas cost for electric utilities and independent power producers, for the United States and for each state. For missing values, we use state average.	Catalyst Cooperative (2021) based on EIA (2020), FERC (2020) EIA (2019,2020) Carbon Tracker estimate
Carbon price	RGGI costs included for applicable states (Connecticut, California, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Rhode Island, Vermont, Virginia). We forecast a carbon price of \$10.12/tCO_2 by 2040. Otherwise, none.	NYISO (2019) Carbon Tracker estimate
Combustion efficiency	Unit-level efficiency data for 2017-2019 via PUDL. For missing values, we use technology averages. For 2020 onwards we use the average between the previous three years. Gross, low heating value (LHV) adjusted for unit age. Baseline values are boiler type specific: 42% for OCGT, 60% for CCGT (from Ricardo-AEA, 2012) and 35% for ST (from EIA, 2018). The value for each modelled year is adjusted by an annual factor of 0.46%, commencing from the start year of the unit, as indicated in GE Power Systems' report (2000).	Catalyst Cooperative (2021) based on EIA (2020), FERC (2020) Carbon Tracker estimate Ricardo (2015) EIA (2018) GE Power Systems (2000)
Efficiency adjustments from cooling and pollution controls	Adjustments made to the overall combustion efficiency of the plant depending on the technology installed.	EPA (2018)
Environmental control technology capital and operational costs	These costs include fixed operations and maintenance (\$/kW per year) and variable operations and maintenance (\$/MWh). Adjusted for pollutant and nameplate capacity of plant.	EPA (2018)
Unabated coal-fired power generation pathway for below 2°C scenario	We take the IEA B2DS projections for coal generation within the United States.	IEA (2017) Carbon Tracker estimate
Pollution limit regulations and associated capital and operational costs	EPA and regulations associated with the Clean Air Act specifies limits for pollutant emissions rates.	EPA (2018) EPA (2014)
Plant revenues	Wholesale market data for 2017-2020 provided by the EIA at various hubs. We assume that all regulated units have passthrough fixed and variable costs, as well as regulated rates of return based on their estimated rate base (in turn based on straight line depreciation of initial capital cost estimates), while merchant units are paid wholesale market prices. Capacity payments in the US are modelled at Regional Transmission Organisation (RTO) level and applied only to the merchant units we have included (59% of US model). Due to the lack of transparency on capacity contracts, we assume that all gas units in the grid are eligible for payments. For each RTO, we take the median price of a contract (averaged over all zones) per day and estimate a total payment per unit per year. Specifically in the case of MISO where a fuel breakdown is available, we scale down payments according to the amount of gas capacity awarded and gas capacity modelled in the grid. We cover all contract delivery years awarded as of July 2021. Capacity payments are then assumed to continue at the same level until 2040, after which they are assumed to be phased out.	EIA (2019a) MISO (2018, 2019) S&P Global MI (2019) Carbon Tracker estimate

7.2.2 Renewable LCOE assumptions

PARAMETER	DETAIL	SOURCE
Assumptions for onshore wind		
Capital Expenditure	CAPEX data for onshore wind for USA was sourced from the IRENA 2019 cost publication with the cost breakdown. A lower and upper band was calculated using a 20% assumption.	IRENA (2019)
O&M Costs	O&M costs were assumed to be 1.2% of CAPEX. A lower and upper band was calculated using a 20% assumption.	Carbon Tracker estimate

Capacity factor	Country level capacity factor data was sourced from a REN21 publication which is based on data from the IRENA 2019 cost publication. A lower and upper band was calculated using a 20% assumption. Local capacity factors were calculated with an algorithm that combines global wind resource data from the World bank with land cover data and data on nationally protected areas to filter out inappropriate locations. The resulting local capacity factors were normalised by the country specific capacity factors to account for any project constraints not captured by the algorithm.	REN21 (2019) IRENA (2019) Protected Planet (2019) ESA (2019) Global Wind Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was sourced from NYU Stern.	NYU Stern (2019)
Cost of Debt	Data on long term lending rates was sourced from the World Bank to which 1% was added to account for long term risk while inflation data was sourced from the IMF.	World Bank (2018) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from REMAP file for G20 countries. A learning rate of 17% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2019a)
Assumptions for solar PV		
Capital Expenditure	CAPEX data for solar for USA was sourced from the IRENA 2019 cost publication together with the cost breakdown. Supplementary data from NREL was used to lower the estimate. A lower and upper band was calculated using a 20% assumption.	IRENA (2019) NREL (2019)
O&M Costs	O&M costs were assumed to be 0.7% of CAPEX. A lower and upper band was calculated using a 20% assumption.	Carbon Tracker estimate
Capacity factor	Country capacity factor data was sourced from a REN21 publication which is based on the IRENA 2019 cost publication. Lower and upper bands were calculated using a 20% assumption. Local capacity factors were calculated using solar irradiance data from the World Bank's global solar atlas and normalised by the country capacity factors to account for any constraint's not captured by the local analysis.	REN21 (2019) Global Solar Atlas (2019) Carbon Tracker estimate
Return on Equity	Return on equity was sourced from NYU Stern.	NYU Stern (2019)
Cost of Debt	Data on long term lending rates was sourced from the World Bank to which 1% was added to account for long term risk while inflation data was sourced from the IMF.	World Bank (2018) IMF (2019)
Capacity deployment and learning rate	Data on deployment projections was sourced from REMAP file for G20 countries. A learning rate of 22% and the most aggressive deployment scenario were used to project LCOE to 2040.	IRENA (2019a)

7.3 Battery storage costs

In order to better compare firm sources of electricity to variable souces, such as renewables, we estimate the costs of battery storage attached to a solar or wind plant to provide a backup solution for periods of low generation. Lithium-ion batteries are very efficient, with a discharge rate of more than 90% compared to 40%-50% derived from lead-acid batteries. A four-hour lithium-ion battery is the typical industry standard for backup energy storage. We therefore estimate 4-hour battery storage capital costs of $1405/kW based on an assumed cost of $351/kWh[5]. In order to model the additional costs to our renewable LCOE estimate, we add these capital costs onto the capital costs of the wind or solar project. This assumes that the battery is fully captive to the wind or solar project, a scenario which may not be the most optimal and is therefore a conservative estimate of storage costs.

[5] *Cost Projections for Utility-Scale Battery Storage: 2021 Update, NREL, https://www.nrel.gov/docs/fy21osti/79236.pdf*

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