How to waste over half a trillion dollars

The economic implications of deflationary renewable energy for coal power investments

March 2020

Carbon Tracker Initiative

About Carbon Tracker

The Carbon Tracker is a team of financial specialists making climate risk real in today's 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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About Powering Down Coal 2020 series

This report is the first in a three-part series and follows *Powering Down Coal: Navigating the economic and financial risks in the last years of coal power* published in 2018. The other reports cover the profitability of coal power and the cost to replace and retire the operating coal fleet. All reports draw on the data and analytics from our Global Coal Power Economics Model (GCPEM), a propriety techno-economic simulation model which tracks ~95% of operating, under-construction and planned coal capacity at boiler-level. GCPEM is updated quarterly.

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Key findings

- New investments in renewables are cheaper than new investments coal in all major markets today.
- Over half of coal plants operating today cost more to run than building new renewables.
- It could be cheaper to build renewables than run coal in all major markets by 2030.
- Governments and investors should cancel coal power projects or risk wasting over $600 bn in capital costs.

Summary

This report analyses two economic inflection points critical to understanding the relative competitiveness of coal power.

1 When energy generated via investments in renewables is cheaper than that generated by new investments in coal.

2 When energy generated via new investments in renewables is cheaper than generating energy using existing coal.

In doing so, we find that inflection point one has already occurred in all major markets and inflection point two will have occurred in all major markets by 2030 at the latest. These findings have wholesale implications for coal power investments throughout the world.

Modelling metrics and policy assumptions used in this report

The outputs of this report have been generated by GCPEM, a propriety techno-economic simulation model which tracks ~95% of operating, under-construction and planned coal capacity at boiler-level. To the best of our knowledge GCPEM is the first time anyone has attempted global coverage of coal power at asset-level and made this data publicly available. All demand and supply assumptions are fully described in the GCPEM methodology document and Appendix of this report.

Levelised cost of electricity (LCOE)

LCOE = capital cost + LRMC

The LCOE is a standard analytical tool used to compare power generation technologies and is widely used in power market analysis and modelling. The LCOE is simply the sum of all costs divided by the total amount of generation. The LCOE is based on a discounted cash flow model where costs of developing and running power generation assets that are discounted using a real weighted average cost of capital. Our LCOE estimates for onshore wind and solar photovoltaics (PV) do not consider battery storage but include economic and environmental conditions in each market. See the Appendix and methodology document for more information.

Long-run marginal cost (LRMC)

LRMC = fuel + carbon + variable O&M + fixed O&M

The LRMC is cost of operating a coal unit. Fuel costs include the cost of buying, transporting, and preparing the coal. Carbon costs are based on existing and ratified policies. Variable O&M costs vary with the use of the unit. Fixed O&M costs do not vary with the use of the unit and include capital additions to maintain performance and comply with environmental regulations.

Key policy assumptions

The wind and solar capital costs are mostly obtained from International Renewable Energy Agency (IRENA), with deployment projections (and thus learning rates) being derived from IRENA's REMAP. Capacity factors for wind and solar are from the World Bank's solar and wind atlas, respectively.

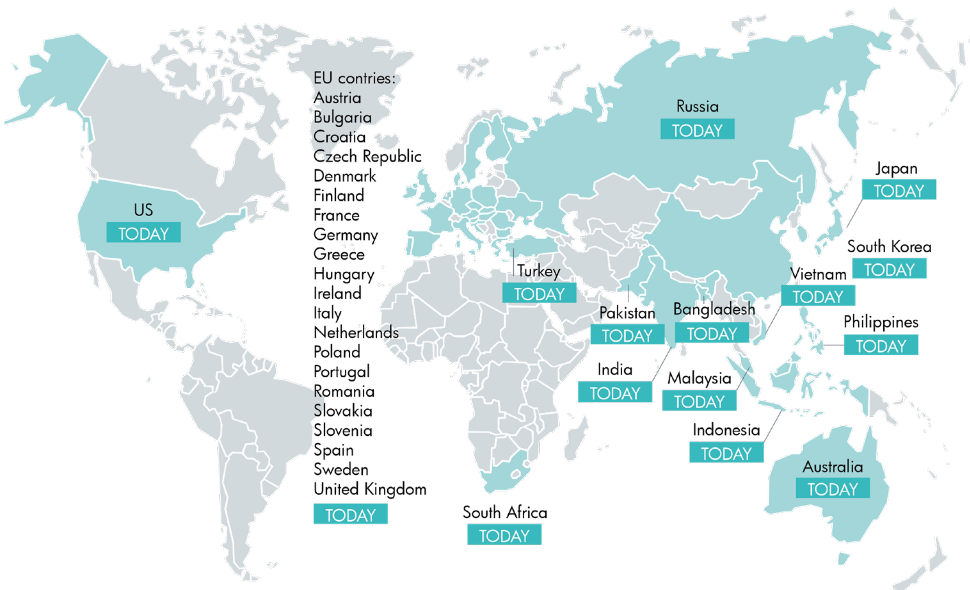
The coal capital costs are obtained from the International Energy Agency (IEA) as well as our estimates. Coal price data is sourced from Bloomberg LP. This data is combined with our transport cost algorithm, which calculates the cost to transport coal based on shipping routes from port to port and land transport routes from port to mine. 2020 onwards assumptions for the operating costs of coal are based on a 2017 to 2019 average.

We only include existing and ratified carbon pricing and air pollution policies. We include carbon pricing regimes in the EU, South Korea, the US (Regional Greenhouse Gas Initiative) and China. We assume the EU ETS price will increase from €25/t today to €40/t by 2030 and the CN ETS will rise from $5/t in 2021 to $40/t by 2040. All other carbon pricing policies are assumed to remain unchanged. Regarding air pollution policies, we assume the following regulations are met through the installation of control technologies: China's emission standard of air pollutants for thermal power plants, the EU's Industrial Emissions Directive, the US's New Source Performance Standards, India's Environment Protection Amendment Rules and Japan's Air Pollution Control Law. All other air pollution policies are assumed to remain unchanged.

New renewables cheaper than new coal in all major markets today

In *Powering Down Coal: Navigating the economic and financial risks in the last years of coal power* published in 2018, we found that declining renewable energy costs and existing carbon and air pollution regulations were already undermining coal as the least-cost option for power generation. Due to price deflation of renewable energy, we concluded that coal generation would become uneconomic in both absolute and relative terms. Regarding the latter, we anticipated that by 2025 at the latest, investments in new renewables would beat new coal investments in all markets. Using updated data from publicly available sources, we now believe these conclusions are too conservative. Our analysis finds that the LCOE of renewable energy is cheaper than the LCOE of coal in all major markets today.

FIGURE 1. REGIONS WHERE NEW RENEWABLE ENERGY IS CHEAPER THAN NEW COAL



Source: Carbon Tracker analysis
Notes: See the body of the report for more detail on specific regions

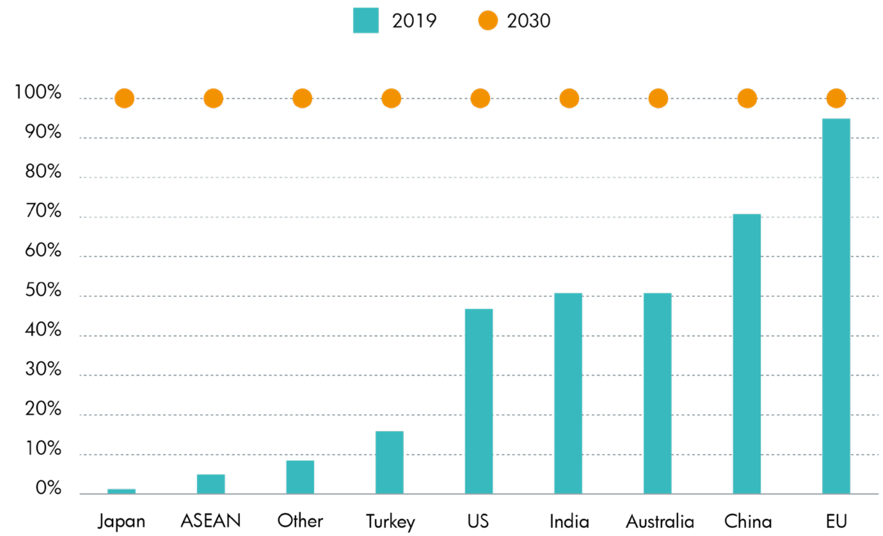
Over half of the operating coal fleet costs more to run than new renewables

The second inflection point, the year when the LCOE of renewables outcompetes the LRMC of coal, is where existing coal will start to become economically obsolete. Our modelling finds that around 60% of the global coal fleet already has a higher LRMC than the LCOE of renewable energy. This trend is most pronounced in the EU, which has a strong carbon price and has benefited from years of investment in renewable energy. The US, China and India are not far behind the EU due to excellent renewable energy resources, low capital costs and least-cost policymaking. In markets where renewable energy has yet to outcompete existing coal this is either due to market nascency or poor policymaking. For example, in several ASEAN markets and Japan, there is still not a route to market reliable enough to attract global capital like EU and US markets.

Cheaper to build renewables than run coal in all markets by 2030

By 2030 at the latest, we expect the average LRMC of coal in all major markets to be higher than the LCOE of renewable energy. Assuming competitive and non-discriminatory market regulations, renewable energy developers will take advantage of the difference between power prices and the LCOE of wind and solar PV. This new dynamic will have implications for power price shape and volatility. Increased variable renewable energy supply will increase price volatility and decrease prices during certain times of the day, forcing coal generators to be flexible during those times to avoid operating at a loss. Greater flexibility increases the LRMC of coal generation, exacerbating the difference between the LCOE of renewable energy.

FIGURE 2. COAL CAPACITY WHICH COSTS MORE TO OPERATE THAN NEW WIND OR SOLAR



Source: Carbon Tracker analysis
Notes: See the body of the report for more detail on specific regions

Cancel coal power projects and deregulate markets or waste $600bn

There is currently 499 GW of coal capacity announced, permitted, pre-permitted and under-construction throughout the world with an overnight investment cost of $638 bn. The economics of coal power is far from straightforward and in an important respect bifurcated. We broadly categorise power markets two ways: deregulated and regulated. Deregulated markets are subject to a competitive wholesale power market where generation activities are completely separated from the rest of the value chain. Regulated markets are not subject to the competitive wholesale power market where generation activities are integrated into the rest of the value chain under the ownership of a vertically integrated utility.[1] Our analysis highlights three trends[2] across these markets:

- Deregulated markets where coal faces imminent economic obsolescence through market forces (for e.g., the EU).
- Semi-regulated markets and regulated markets where corporate welfare results in high cost coal being passed on to a captive consumer base (for e.g., the US).
- Semi-regulated and regulated markets where intractable problems are created due to coal generators selling – or being subsidised to sell – power below the cost of production (for e.g., ASEAN).

TABLE 1. THE COST AND COMPETITIVENESS OF NEW COAL POWER INVESTMENTS THROUGHOUT THE WORLD

Country or region	Under-construction (MW)	Announced, permited and pre-permitted	Capital cost ($/mn)	Year when renewables is cheaper than new coal	Year when renewables is cheaper than operating coal
China	99,710	106,176	158,338	TODAY	TODAY
ASEAN	22,883	55,011	123,930	TODAY	2027
India	36,698	29,327	79,850	TODAY	2020
Turkey	1,465	31,715	64,032	TODAY	2023
Japan	9,269	2,612	31,020	TODAY	2026
EU	4,890	2,700	16,074	TODAY	TODAY
United States	-	-	-	TODAY	TODAY
Other	24,657	71,978	164,818	N/A	N/A
Total	199,572	299,519	638,062	N/A	N/A

Source: Global Energy Monitor Global Coal Plant Tracker (2020), Carbon Tracker analysis

These dynamics in regulated and semi-regulated markets mean new investments in coal may continue and coal generators may not close, despite the economics of alternative power generation technologies. If investors and policymakers decide to build and operate the 499 GW of coal capacity permitted, pre-permitted and under-construction throughout the world, it will not have been the least-cost option in those regions, based on our analysis. Moreover, according to analysis of recent research from the UN's Intergovernmental Panel on Climate Change, global coal use in electricity generation must fall by 80% below 2010 levels by 2030 to limit global warming to 1.5°C.[3]

We offer the following high-level recommendations:

China's post-coronavirus stimulus must avoid costly coal power

The outbreak of coronavirus has struck a significant blow to the Chinese economy. How severe the coronavirus may be will not only depend on the extent and depth of the outbreak but also the government response.[4] Opaque and inappropriate pricing structures for power generation have long been a key distortion in the Chinese economy. For instance, according to Carbon Tracker analysis, around 70% of China's operating coal fleet costs more to run than building new onshore wind or utility-scale solar PV. Despite this, China has 99.7 GW of coal-fired capacity under-construction and another 106. 1 GW of capacity in various stages of the planning process. The National Energy Administration's recent circular on coal power planning and construction implies policymakers are prepared to approve investments in coal in the near future.[5] China's authoritarian governance means it can deploy capital effectively and do so in a way that does not stifle innovation. China must seize the opportunity and act on the risk by deploying stimulus capital efficiently and avoid investing in coal power which is economically redundant and environmentally disastrous.

Governments and investors need to act on the risk: cancel projects to avoid stranded cost risk

Investors are increasingly recognising inflection point one and are responding by restricting thermal coal funding.[6] However, several governments are continuing to incentivise and underwrite coal projects. The capital recovery period for new investments in coal capacity is typically 15 to 20 years, making these investments extremely risky given our finding that coal will not be a least cost option before debt is fully amortized. The large difference between the LCOE of renewable energy and the LCOE and LRMC of coal make it highly unlikely that these investments will be any less risky when system costs are considered. Therefore, governments – and investors who are relying on government-backed power purchase agreements (PPAs) – need to urgently reconsider these coal projects in light of prevailing economics. Table 2 details the level of stranded cost risk by region and offers high-level policy recommendations.

1 *There are also semi-regulated markets are either transitioning from regulated to deregulated, or hybrid markets with both regulated and deregulated characteristics.*
2 *See the Appendix for a definition of regulated, semi-regulated and deregulated markets.*

3 https://climateanalytics.org/briefings/coal-phase-out/
4 https://www.brookings.edu/wp-content/uploads/2020/03/20200302_COVID19.pdf
5 https://chinaenergyportal.org/en/circular-on-2023-risk-and-early-warning-for-coal-power-planning-and-construction/
6 https://ieefa.org/finance-exiting-coal/

TABLE 2. LEVEL OF STRANDED RISK BY REGION AND HIGH LEVEL POLICY RECOMMENDATIONS

Country or region	Market type	Stranded cost risk	Policy recommendation
China	Regulated and semi-regulated	Extreme	Cancel all under-construction and planned capacity immediately. Increase utilisation rate of existing fleet through selective retirements in oversupplied or uncompetitive provinces. Request our asset-level below 2°C or Paris-aligned phase-out schedules here.
India	Regulated	Extreme	Cancel all under-construction and planned capacity immediately. Request our asset-level below 2°C or Paris-aligned phase-out schedules here.
ASEAN	Regulated and semi-regulated	Moderate	Rationalise under-construction and planned capacity by cancelling all projects that have stranded cost risk before the end of the debt amortisation schedule. Request our asset-level below 2°C or Paris-aligned phase-out schedules here.
Turkey	Regulated	High	Cancel all under-construction and planned capacity. Request our asset-level below 2°C or Paris-aligned phase-out schedules here.
Japan	Semi-regulated	High	Cancel all under-construction and planned capacity. Request our asset-level below 2°C or Paris-aligned phase-out schedules here.
EU	Deregulated	Extreme	Cancel all under-construction and planned capacity immediately. Request our asset-level below 2°C or Paris-aligned phase-out schedules here.
US	Regulated, semi-regulated and deregulated	Extreme	The US has no new coal in the project pipeline. Request our asset-level below 2°C or Paris-aligned phase-out schedules here.

Source: Carbon Tracker analysis

Stranded cost risk definition	
Extreme	45% or more of coal capacity that costs more to operate than new renewable energy today and 100% by 2030.
High	25-45% of coal capacity that costs more to operate than new renewable energy today and 100% by 2030.
Moderate	10-25% of coal capacity that costs more to operate than new renewable energy today or 45% or more by 2030.
Low	10% or less of coal capacity that costs more to operate than new renewable energy today and 45% or less by 2030.

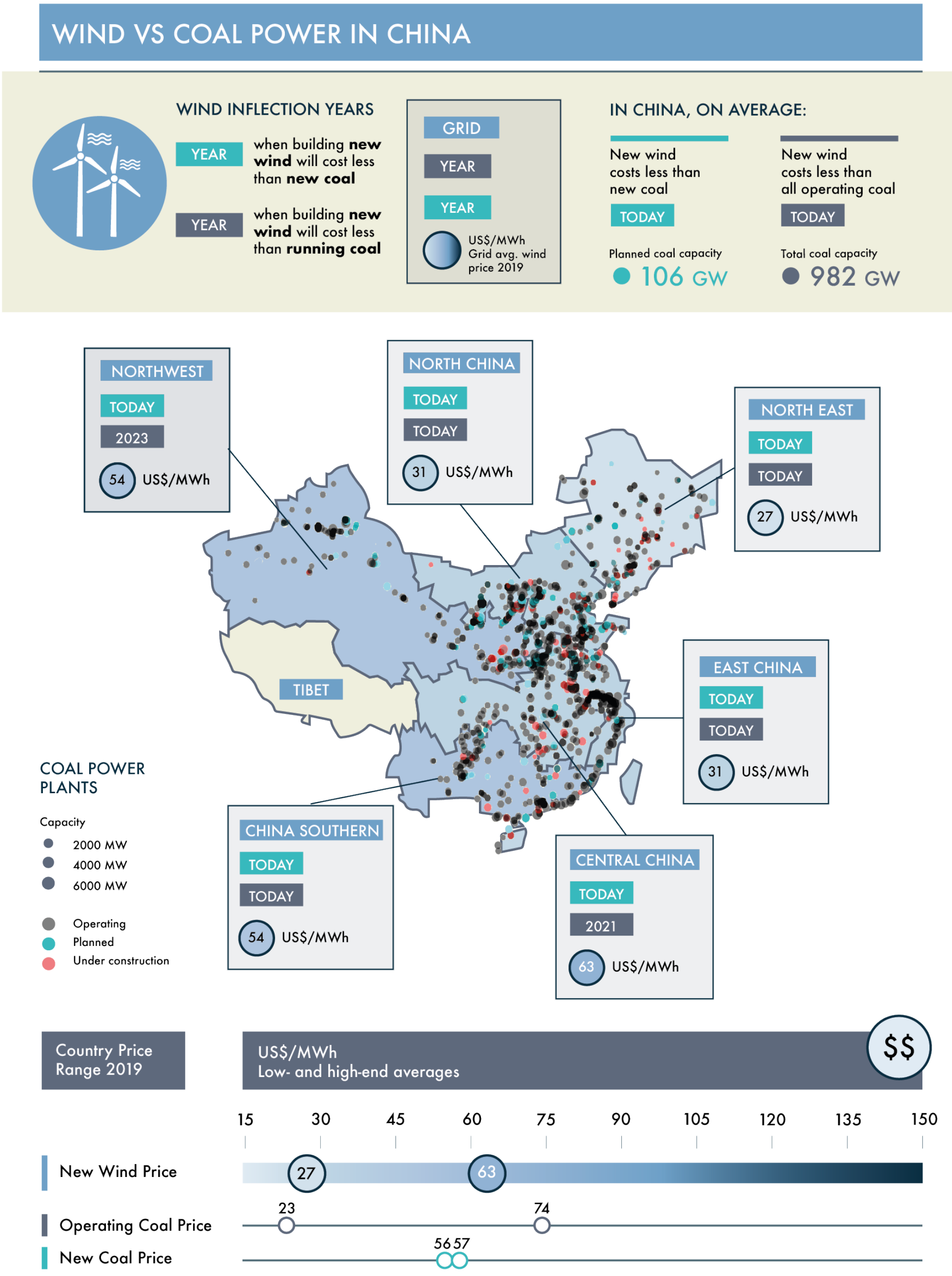
Policymakers need to increase price discovery to incentivise least-cost power generation technologies

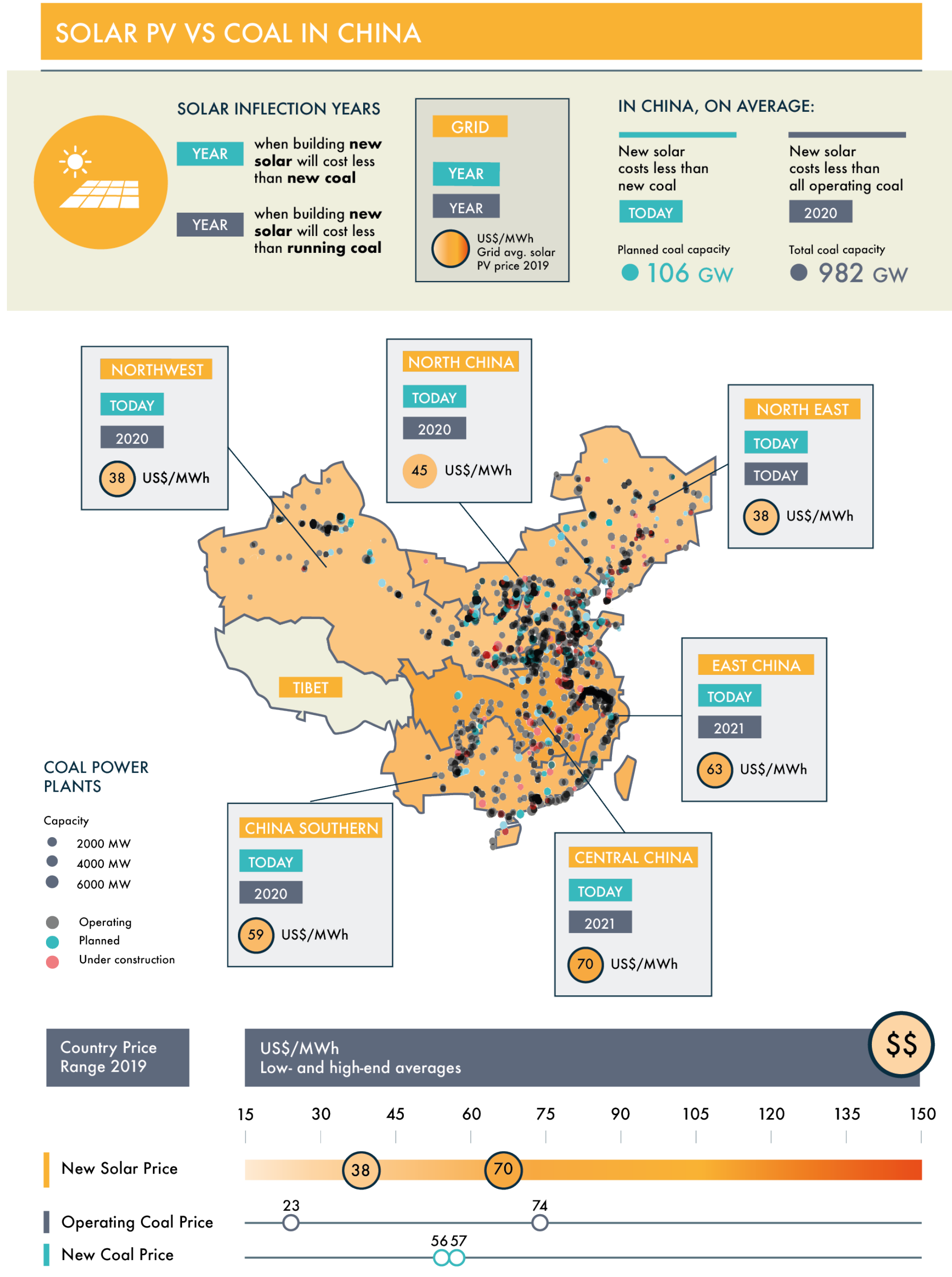
Price discovery – i.e. determining the value of an asset in the marketplace through the interactions of buyers and sellers – is often limited in regulated and semi-regulated markets. Investment decisions tend to be made based on PPAs, and governments are predisposed to keep coal capacity operating for socioeconomic reasons. This dynamic means new investments in coal may continue, allowing coal generators to continue to operate despite the increasingly undisputable economic advantages of alternative power generation technologies. Policymakers urgently need to deregulate power markets to ensure least-cost power generation technologies are built as a priority.

Seize the opportunity: introduce phase-out schedules to avoid creating a negative investment signal for renewable energy

As well as disincentivising new builds, policymakers need to introduce regulations that maximise the systems value of variable renewable energy and retire the existing coal fleet through phase-out schedules. Failure to take these steps will exacerbate stranded asset risk and could result in overcapacity. This, in turn, will suppress power prices, create a negative investment signal for renewable energy and ultimately stifle the transition to a low carbon economy.

Regional maps - the main markets*





*All regional maps are based on 2019 data

Source: Carbon Tracker analysis

Source: Carbon Tracker analysis

WIND VS COAL POWER IN INDIA

WIND INFLECTION YEARS

YEAR — when building **new wind** will cost less than **new coal**

YEAR — when building **new wind** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. wind price 2019

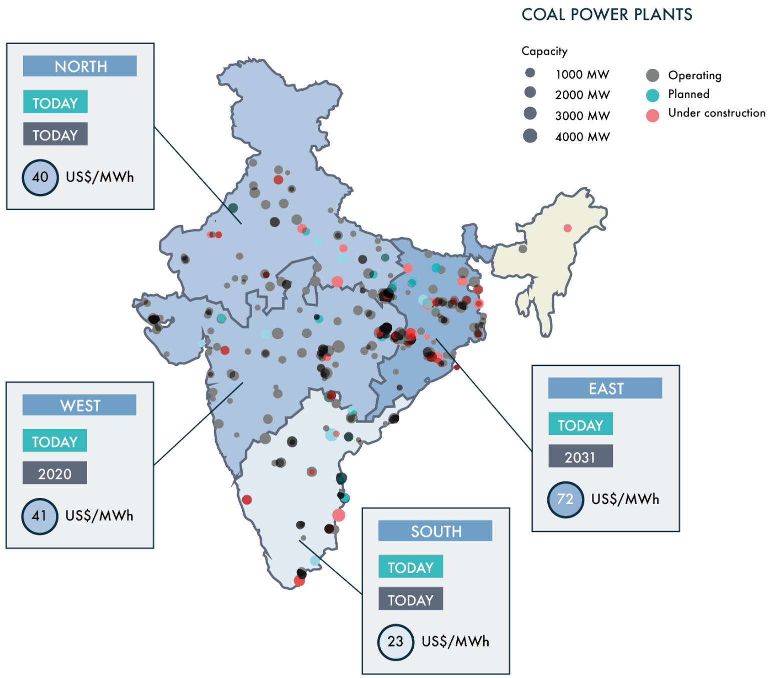
IN INDIA, ON AVERAGE:

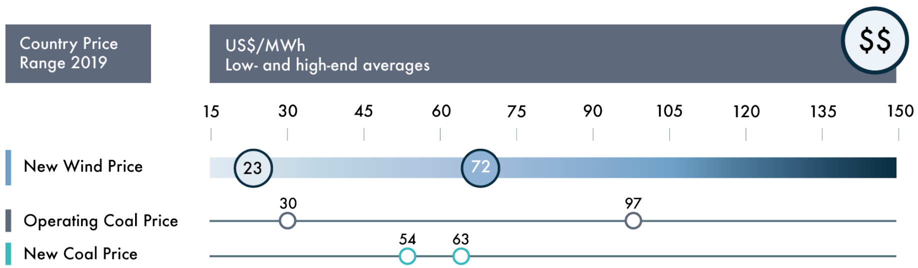
New wind costs less than new coal: TODAY

New wind costs less than all operating coal: 2022

Planned coal capacity: 29 GW

Total coal capacity: 222 GW





Source: Carbon Tracker analysis

SOLAR PV VS COAL IN INDIA

SOLAR INFLECTION YEARS

YEAR — when building **new solar** will cost less than **new coal**

YEAR — when building **new solar** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. solar PV price 2019

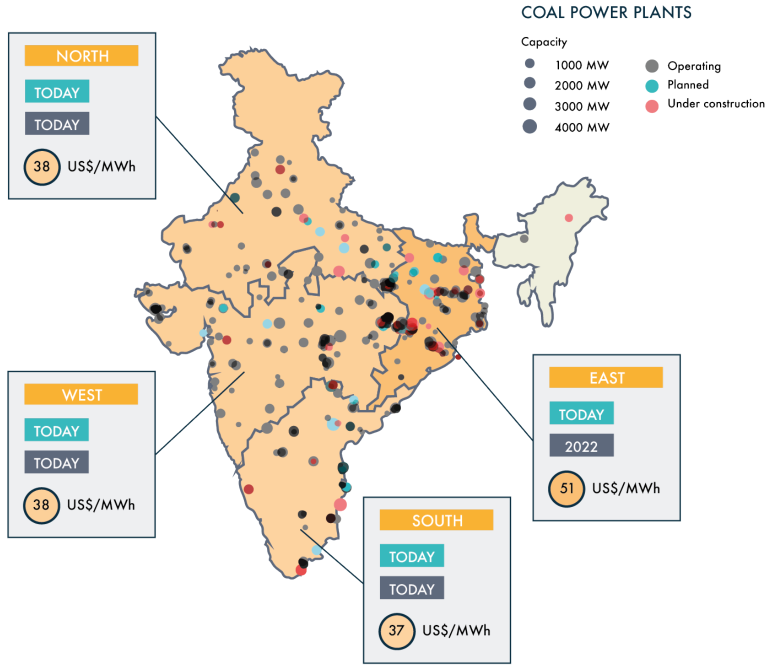
IN INDIA, ON AVERAGE:

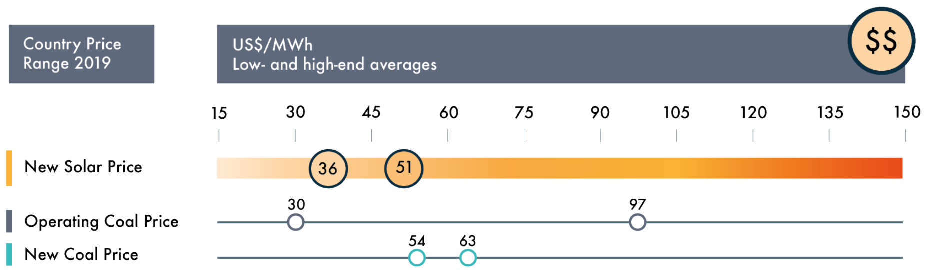
New solar costs less than new coal: TODAY

New solar costs less than all operating coal: 2020

Planned coal capacity: 29 GW

Total coal capacity: 222 GW





Source: Carbon Tracker analysis

WIND VS COAL POWER IN EUROPE

WIND INFLECTION YEARS

YEAR — when building **new wind** will cost less than **new coal**

YEAR — when building **new wind** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. wind price 2019

IN EUROPE, ON AVERAGE:

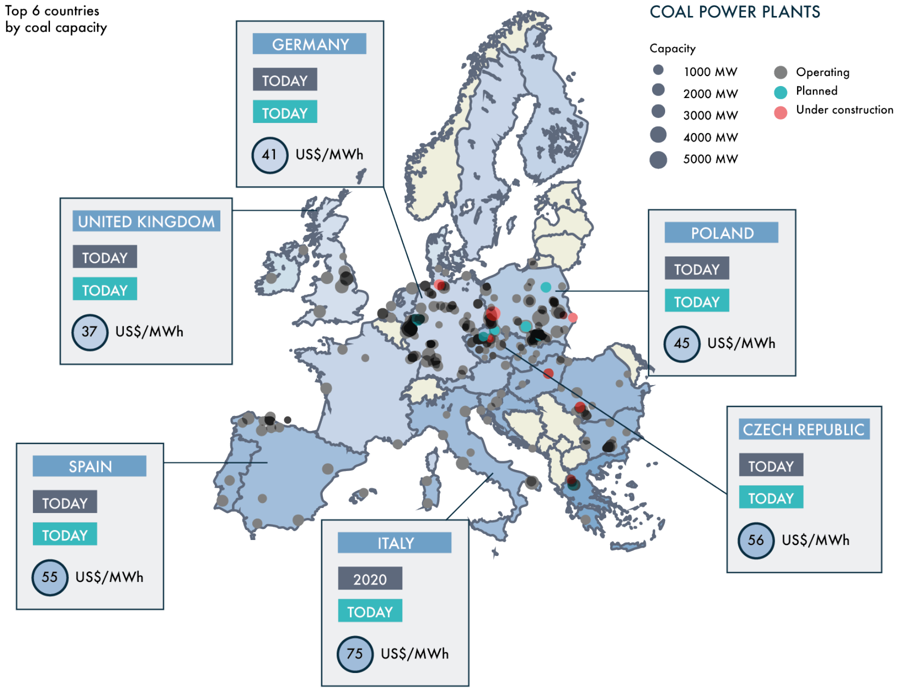
New wind costs less than new coal — TODAY

New wind costs less than all operating coal — TODAY

Planned coal capacity: 3 GW

Total coal capacity: 149 GW

Top 6 countries by coal capacity



Country Price Range 2019

US$/MWh Low- and high-end averages $$

15 30 45 60 75 90 105 120 135 150 165 180 195 210

New Wind Price: 27 – 106

Operating Coal Price: 53 – 183

New Coal Price: 67 – 201

Source: Carbon Tracker analysis

SOLAR PV VS COAL IN EUROPE

SOLAR INFLECTION YEARS

YEAR — when building **new solar** will cost less than **new coal**

YEAR — when building **new solar** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. solar PV price 2019

IN EUROPE, ON AVERAGE:

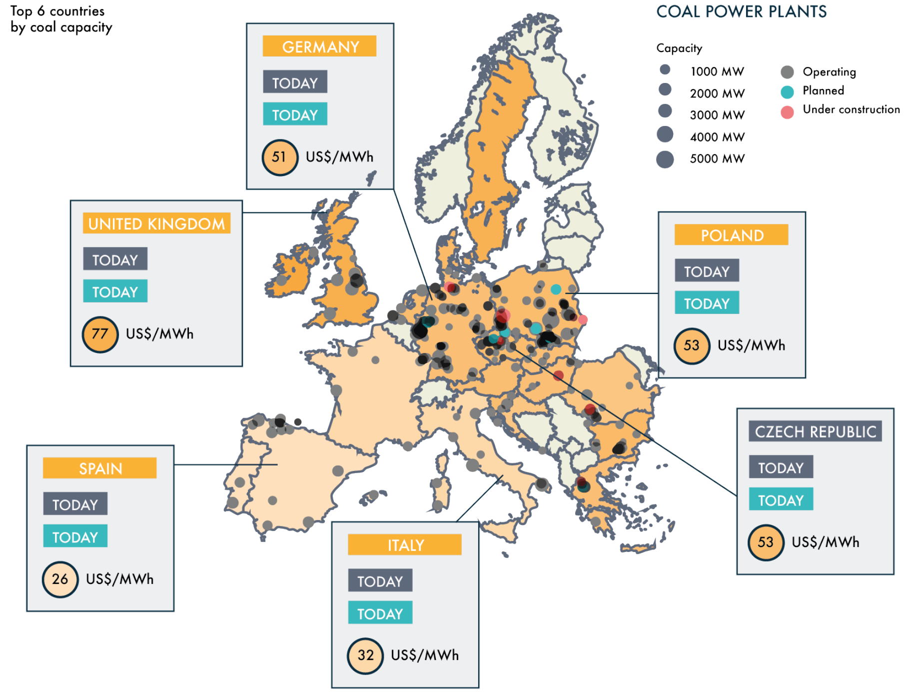
New solar costs less than new coal — TODAY

New solar costs less than all operating coal — TODAY

Planned coal capacity: 3 GW

Total coal capacity: 149 GW

Top 6 countries by coal capacity



Country Price Range 2019

US$/MWh Low- and high-end averages $$

15 30 45 60 75 90 105 120 135 150 165 180 195 210

New Solar Price: 26 – 88

Operating Coal Price: 53 – 183

New Coal Price: 67 – 201

Source: Carbon Tracker analysis

WIND VS COAL POWER IN JAPAN

WIND INFLECTION YEARS

YEAR when building **new wind** will cost less than **new coal**

YEAR when building **new wind** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. wind price 2019

IN JAPAN, ON AVERAGE:

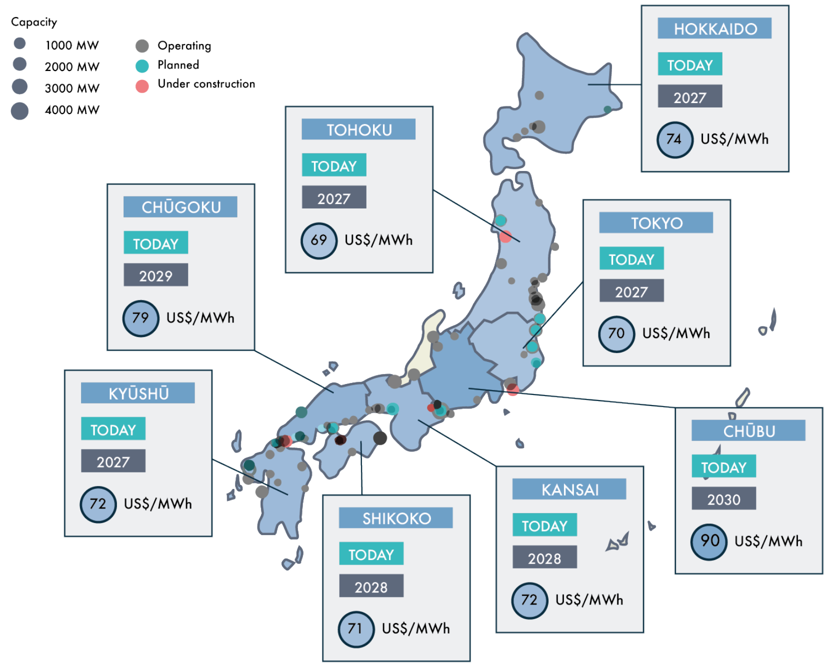
New wind costs less than new coal: **TODAY**

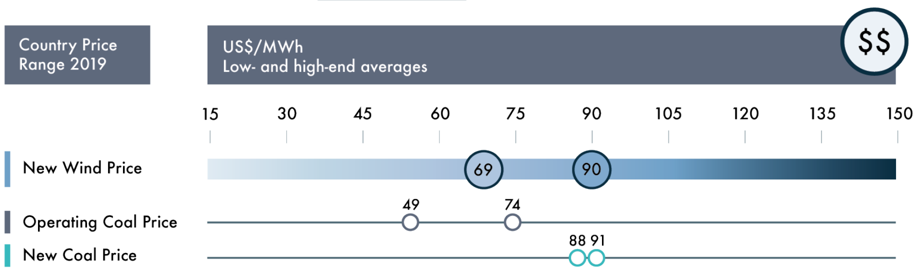
New wind costs less than all operating coal: **2028**

Planned coal capacity: 3 GW

Total coal capacity: 45 GW

COAL POWER PLANTS





Source: Carbon Tracker analysis

SOLAR PV VS COAL IN JAPAN

SOLAR INFLECTION YEARS

YEAR when building **new solar** will cost less than **new coal**

YEAR when building **new solar** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. solar PV price 2019

IN JAPAN, ON AVERAGE:

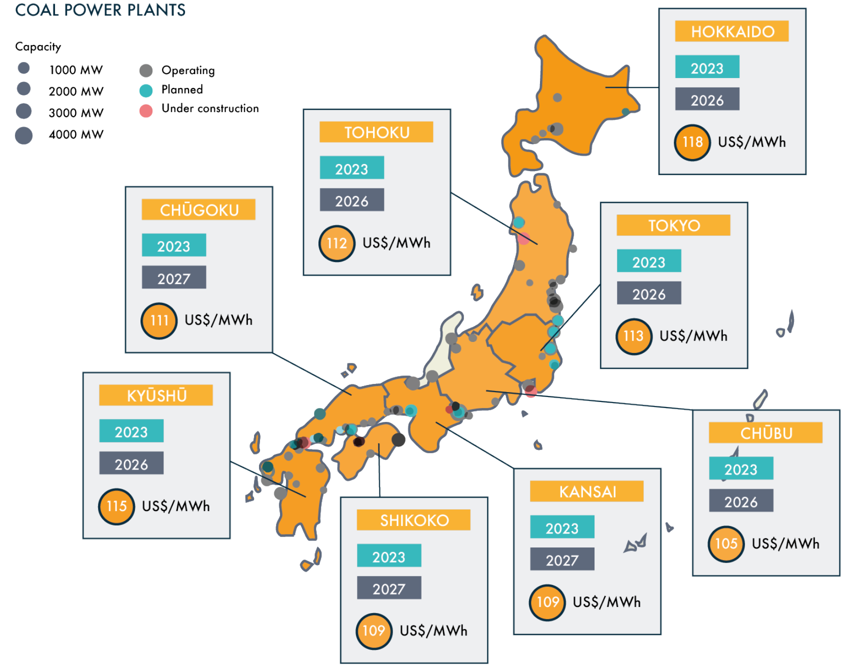
New solar costs less than new coal: **2023**

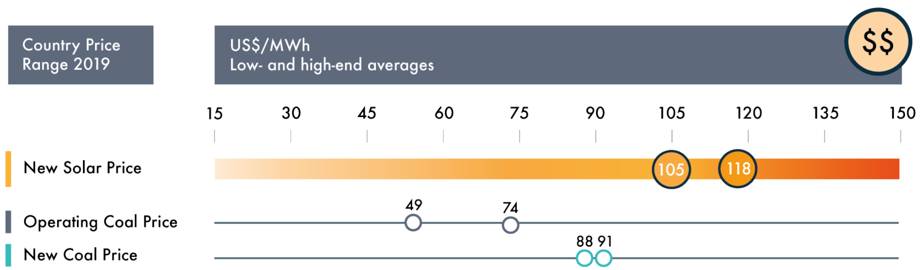
New solar costs less than all operating coal: **2026**

Planned coal capacity: 3 GW

Total coal capacity: 45 GW

COAL POWER PLANTS





Source: Carbon Tracker analysis

WIND VS COAL POWER IN THE UNITED STATES

WIND INFLECTION YEARS

YEAR when building **new wind** will cost less than **new coal**

YEAR when building **new wind** will cost less than **running coal**

GRID

YEAR

YEAR

US$/MWh Grid avg. wind price 2019

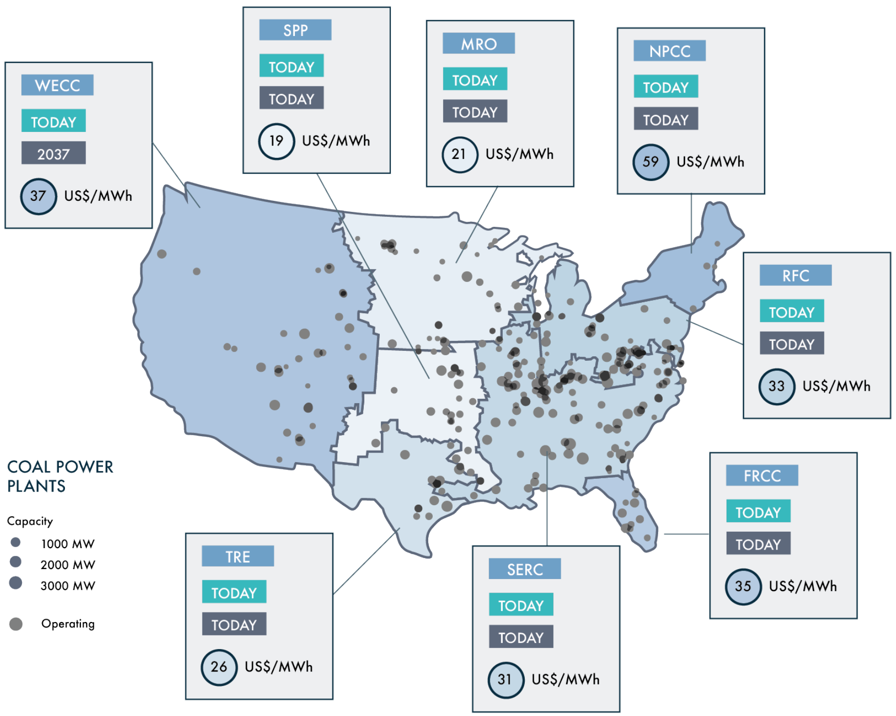
IN THE US, ON AVERAGE:

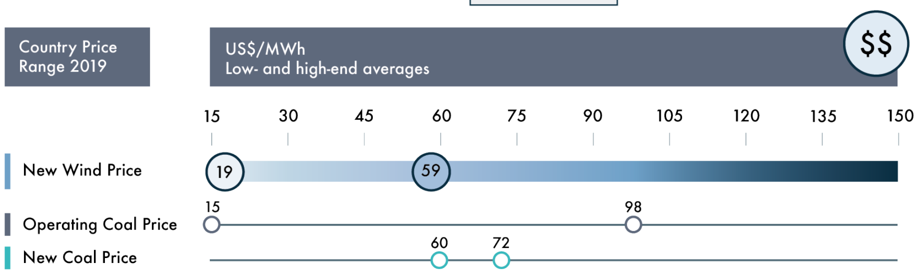
New wind costs less than new coal: TODAY

New wind costs less than all operating coal: TODAY

Planned coal capacity: N/A

Total coal capacity: 254 GW





Source: Carbon Tracker analysis

SOLAR PV VS COAL IN THE UNITED STATES

SOLAR INFLECTION YEARS

YEAR when building **new solar** will cost less than **new coal**

YEAR when building **new solar** will cost less than **running coal**

GRID

YEAR

YEAR

US$/MWh Grid avg. solar PV price 2019

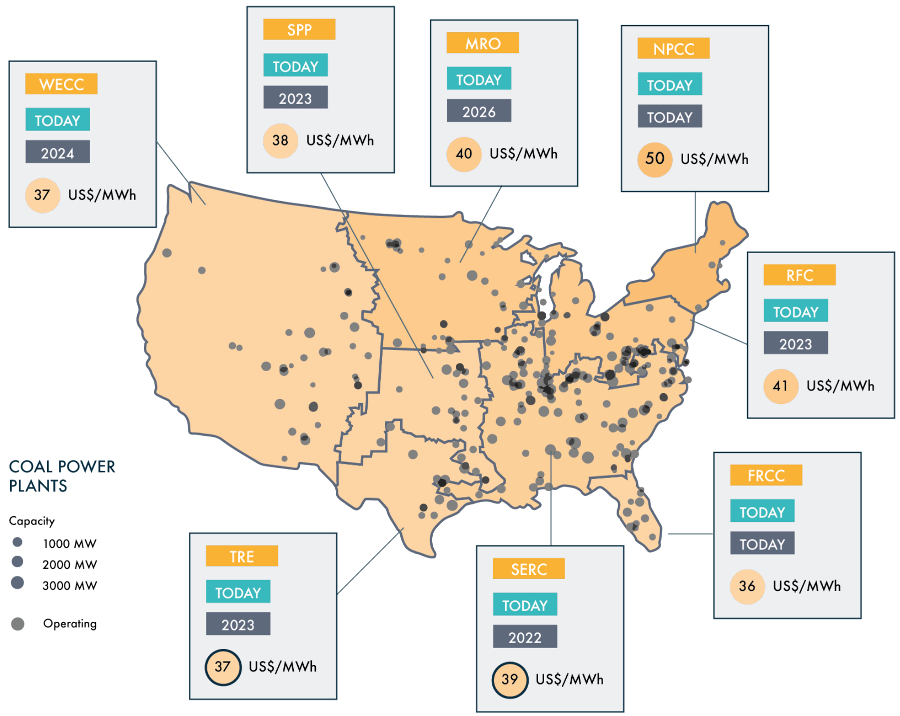
IN THE US, ON AVERAGE:

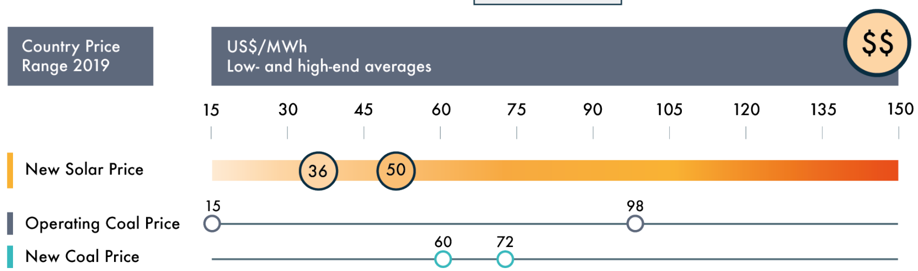
New solar costs less than new coal: TODAY

New solar costs less than all operating coal: TODAY

Planned coal capacity: N/A

Total coal capacity: 254 GW





Source: Carbon Tracker analysis

WIND VS COAL POWER IN THE ASEAN COUNTRIES

WIND INFLECTION YEARS

YEAR — when building **new wind** will cost less than **new coal**

YEAR — when building **new wind** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. wind price 2019

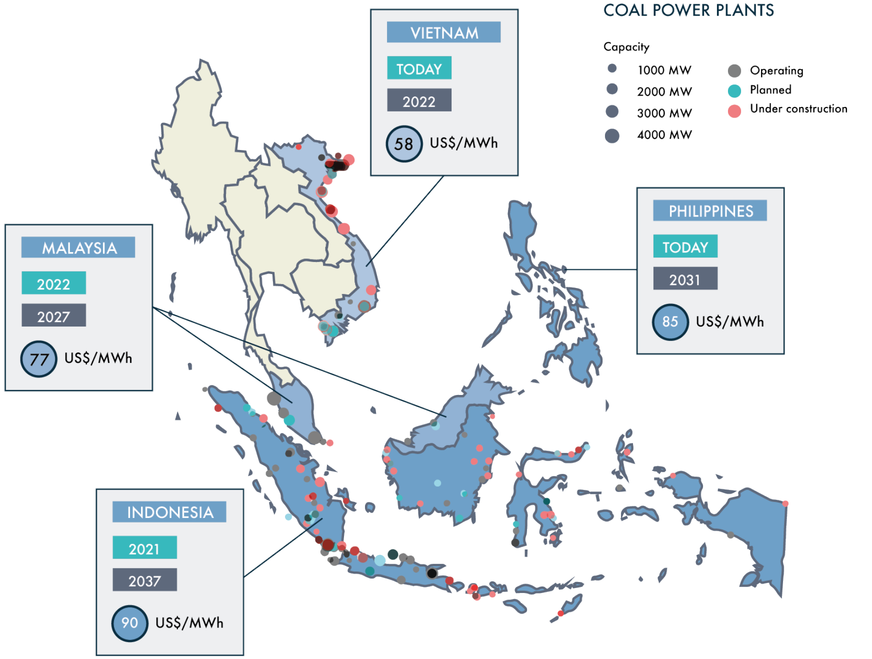
IN ASEAN, ON AVERAGE:

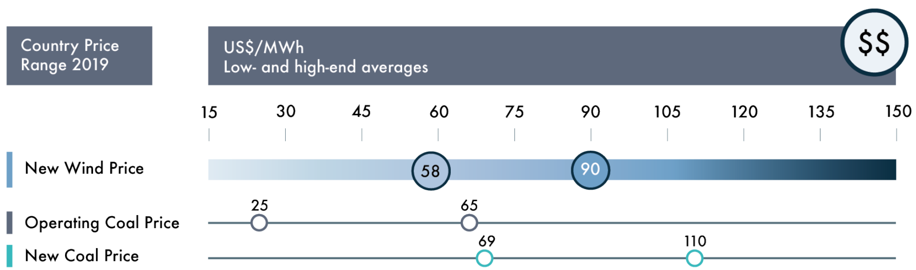
New wind costs less than new coal — 2020

New wind costs less than all operating coal — 2036

Planned coal capacity: 55 GW

Total coal capacity: 66 GW





Source: Carbon Tracker analysis

SOLAR PV VS COAL IN THE ASEAN COUNTRIES

SOLAR INFLECTION YEARS

YEAR — when building **new solar** will cost less than **new coal**

YEAR — when building **new solar** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. solar PV price 2019

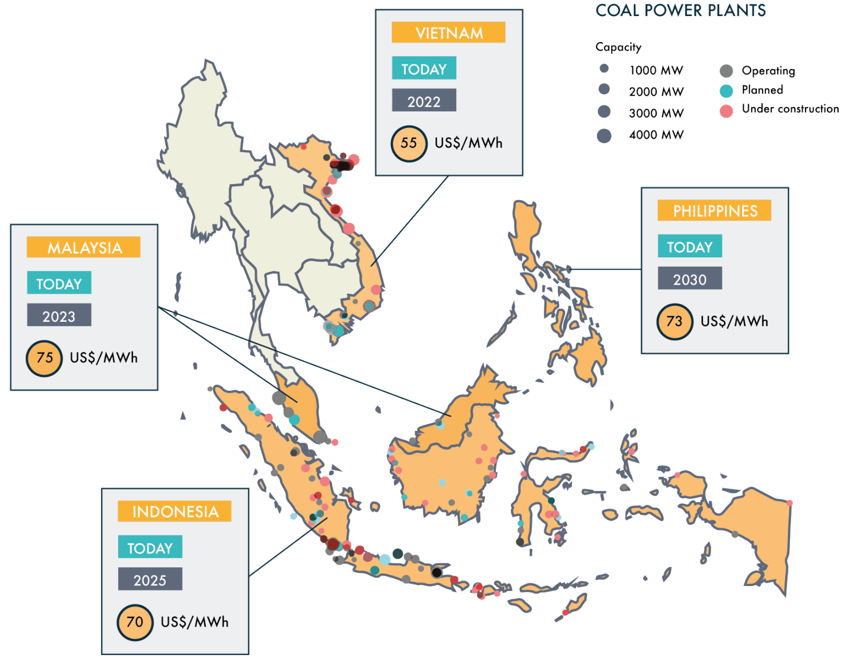
IN ASEAN, ON AVERAGE:

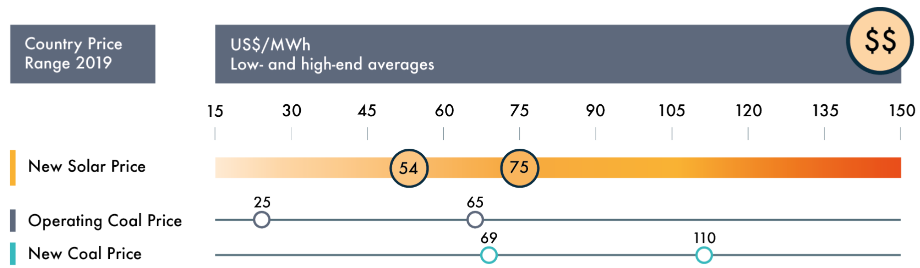
New solar costs less than new coal — TODAY

New solar costs less than all operating coal — 2027

Planned coal capacity: 55 GW

Total coal capacity: 66 GW





Source: Carbon Tracker analysis

WIND VS COAL POWER IN TURKEY

WIND INFLECTION YEARS

YEAR when building **new wind** will cost less than **new coal**

YEAR when building **new wind** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. wind price 2019

IN TURKEY, ON AVERAGE:

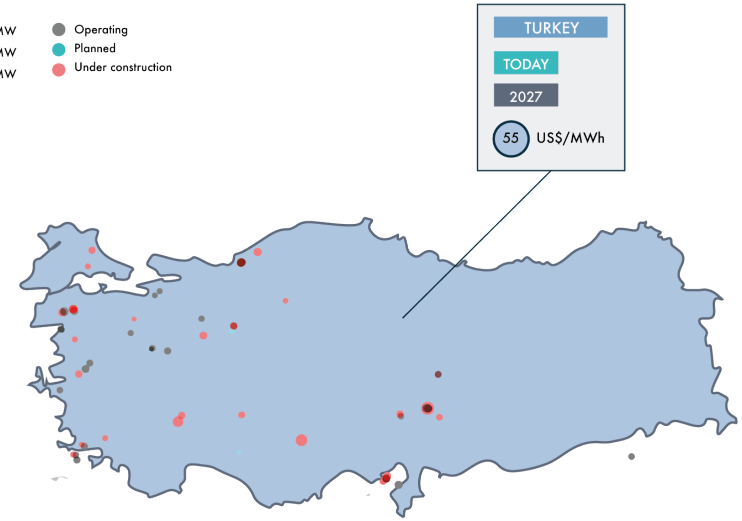
New wind costs less than new coal
TODAY
Planned coal capacity
32 GW

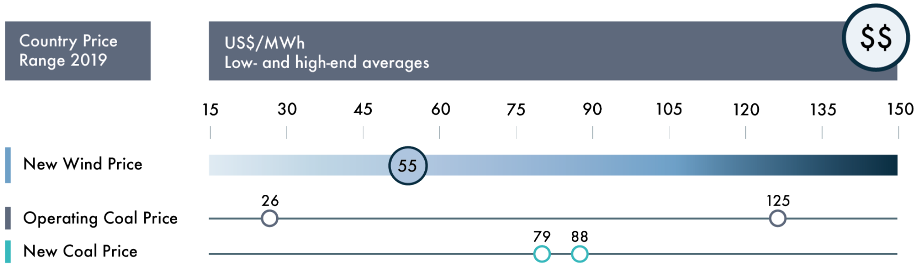
New wind costs less than all operating coal
2027
Total coal capacity
19 GW

COAL POWER PLANTS

Capacity
2000 MW
4000 MW
6000 MW

Operating
Planned
Under construction





Source: *Carbon Tracker analysis*

SOLAR PV VS COAL IN TURKEY

SOLAR INFLECTION YEARS

YEAR when building **new solar** will cost less than **new coal**

YEAR when building **new solar** will cost less than **running coal**

GRID
YEAR
YEAR
US$/MWh Grid avg. solar PV price 2019

IN TURKEY, ON AVERAGE:

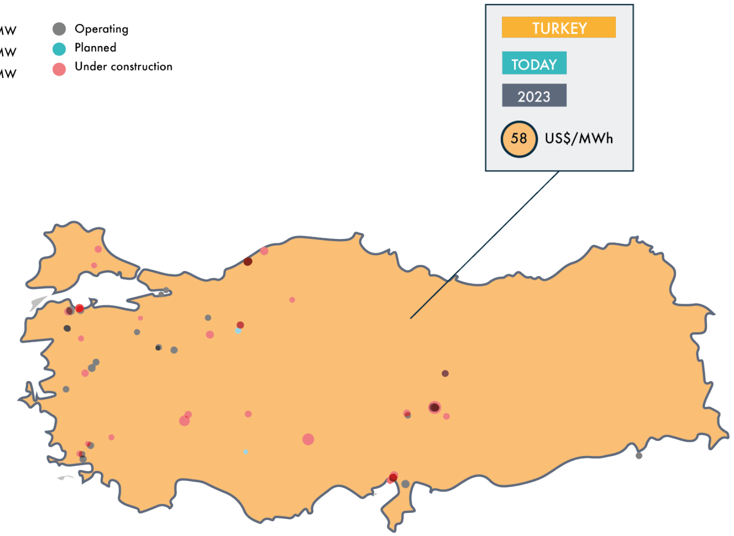
New solar costs less than new coal
TODAY
Planned coal capacity
32 GW

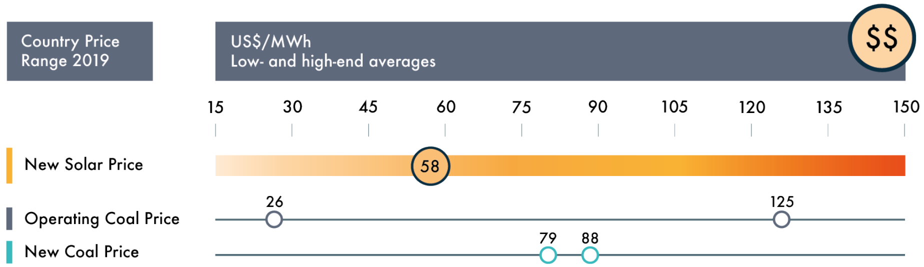
New solar costs less than all operating coal
2023
Total coal capacity
19 GW

COAL POWER PLANTS

Capacity
2000 MW
4000 MW
6000 MW

Operating
Planned
Under construction





Source: *Carbon Tracker analysis*

Other nations

New renewables costs less than new coal — New renewables costs less than operating coal

Australia TODAY TODAY

According to our modelling, it is already cheaper to invest in new renewables than continue to build new coal or operate existing coal in Australia.

Bangladesh TODAY 2022

According to our modelling, it is already cheaper to invest in new renewables than continue to build new coal in Bangladesh. It will be cheaper to invest in new renewables than to operate existing coal in 2022.

Pakistan TODAY TODAY

According to our modelling, it is already cheaper to invest in new renewables than continue to build new coal or operate existing coal in Pakistan.

Russia TODAY 2022

According to our modelling, it is already cheaper to invest in new renewables than continue to build new coal in Russia. It will be cheaper to invest in new renewables than to operate existing coal in 2022.

South Africa TODAY 2027

According to our modelling, it is already cheaper to invest in new renewables than continue to build new coal in South Africa. It will be cheaper to invest in new renewables than to operate existing coal in 2027.

South Korea TODAY 2022

According to our modelling, it is already cheaper to invest in new renewables than continue to build new coal in South Korea. It will be cheaper to invest in new renewables than to operate existing coal in 2022.

Ukraine TODAY 2021

According to our modelling, it is already cheaper to invest in new renewables than continue to build new coal in the Ukraine. It will be cheaper to invest in new renewables than to operate existing coal in 2021.

Source: Carbon Tracker analysis

Conclusion

This report analyses two inflection points critical to understand the relative competitiveness of coal power. The first inflection point considered when new investments in renewable energy (either onshore wind, offshore wind or utility-scale solar PV) are cheaper than new coal. The second inflection point considered when new investments in renewable energy cost less than the operating cost of coal power. Coal has long been considered the least-cost option for power generation throughout the world. This narrative is quickly changing as a confluence of factors are disrupting coal's pre-eminence. Most notably, low-cost renewable energy, which will soon be cheaper to build than to run coal plants. Policymakers need to stop new investments in coal power immediately and redesign power market regulation to minimise stranded asset risk and accelerate the transition to a low carbon economy.

Appendix 1 – Coal capital costs

TABLE 3. OVERNIGHT INVESTMENT COSTS OF BOILER TECHNOLOGIES

	Sub-critical	Super-critical	Ultra-super critical	Lignite	IGCC	CFB	CCS
Europe	1700	2000	2200	1700	2500	2000	3600
US	1800	2100	2300	1800	2600	2100	3780
Canada	1700	2000	2200	1700	2500	2000	3600
Mexico	1500	1800	2000	1500	2300	1800	3240
Chile	1500	1800	2000	1500	2300	1800	3240
Australia	1700	2000	2200	1700	2500	2000	3600
Japan	2100	2400	2600	2100	2900	2400	4320
Korea	1500	1800	2000	1500	2300	1800	3240
Russia	1700	2000	2200	1700	2500	2000	3600
China	600	700	800	600	1100	700	1260
India	1000	1200	1400	1000	1700	1200	2160
Indonesia	1300	1600	1800	1300	2100	1600	2880
ASEAN	1300	1600	1800	1300	2100	1600	2880
Other Asia	1300	1600	1800	1300	2100	1600	2880
Brazil	1300	1600	1800	1300	2100	1600	2880
Other LAM	1300	1600	1800	1300	2100	1600	2880
North Africa	1300	1600	1800	1300	2100	1600	2880
South Africa	1300	1600	2000	1300	2300	1600	2880
Other Africa	1300	1600	1800	1300	2100	1600	2880
Middle East	1300	1600	1800	1300	2100	1600	2880

Source: IEA and Carbon Tracker estimates

Appendix 2 – Metric definitions

LCOE

The LCOE is a standard analytical tool used to compare power generation technologies and is widely used in power market analysis and modelling.[7] The LCOE of PV solar and wind is simply the sum of all costs divided by the total amount of generation. The LCOE calculations in this model are based on a discounted cash flow model where costs (CAPEX and O&M) of developing and running renewable energy assets that are discounted using a real weighted average cost of capital (rWACC). These costs are then divided by the discounted (also using rWCC) lifetime production (in kWh) of the asset to obtain the LCOE value. The rWACC is calculated using a split between debt and equity to finance the project; this is usually 80% debt and 20% equity for OECD countries. The percentage split for debt is then multiplied with the cost of debt, and the inflation rate is subtracted from the total. The percentage equity split is multiplied by the return on equity minus the inflation rate. The sum of these two values yields the rWACC.

Our LCOE methodology differs from other country or region-wide forecasts and involves three steps (see Box p. 32). Firstly, for solar PV, our algorithm extracts irradiance data based on coal plant locations. The capacity factors calculated from this are applied to our country and regional estimates to get local a LCOE for each coal plant.[8] For solar PV, there was no need to sample around plants or filter out locations based on land use because irradiance does not vary much over short distances, meaning point capacity factors closely approximate local maxima. Wind capacity factors on the other hand vary significantly over very short distances because topography significantly affects wind speeds. To obtain good coverage of potential project locations in grid connectible range, we sampled 1,000 points in a 15km radius around each plant with capacity factors by location.[9] The maximum capacity factors among these points for both solar PV and wind were selected after filtering out protected, urban and water covered areas using global databases on protected areas[10] and land use.[11]

Secondly, both solar and wind capacity factors were normalised by country level estimates before being combined with the country level inputs to calculate a unit LCOE estimate. In most regions, renewables to be uneconomic near coal plants as site decisions were not based on wind speeds or solar irradiance in mind. We apply the 20th percentile of the unit LCOEs in each grid to all units in that grid. This modelling approach is based on the notion that a coal unit's capacity could be replaced by renewables at the best location in its grid. Connection

7 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.

8 http://globalsolaratlas.info/map

9 https://globalwindatlas.info/downloads/gis-files

10 https://www.protectedplanet.net/

11 https://www.esa-landcover-cci.org/?q=node/197 will not be prohibitively costly at such locations because each location is a maximum of 15km from a coal unit.

Thirdly, wind and solar capacity factors were normalised by country-level capacity factors. This is an important step (especially for wind) for a number of reasons:

1. Our area-filtering algorithm for wind spots ignores many of the practical constraints on selecting wind locations. There was a systematic tendency for a grid's wind capacity factors to be much higher than the corresponding country estimates. Since the latter are based on real projects, it is likely that the original filtering method – removing urban, water filled and protected areas – was not strict enough. By normalising, relative differences are accounted for between geographies while guarding against any optimism bias in the unit methods.

2. The capacity factors from global wind atlas (see Footnote 6) are based on three turbine types, whereas in reality the turbine type will depend on wind speeds and any regulatory constraints. A single type was chosen for consistency.[12] Combined with the fact that the relative magnitudes of capacity factors do not differ significantly between turbine classes, this means normalisation will give reasonably accurate costs.[13]

Local solar estimates showed the opposite trend to wind estimates in that grid capacity factors were slightly lower than the corresponding country level estimates. For wind, this is offset by the fact that wind varies so much locally, making it easy to find pockets of high wind speeds in a high-resolution map even if these may not be practical locations[14] even if these may not be practical locations. Normalisation corrects for these biases irrespective of the bias direction because the country estimates are based on real projects. Relative differences by geography are retained.

The difference between Carbon Tracker and other country-level estimates

The differences observed between country level LCOE estimates, such as BNEF, IRENA and IEA, and CTI country level LCOE stem from the differences between the data entering the calculations. BNEF, as IRENA does, uses project level data to calculate a nation average, namely cost data on projects built and commissioned in 2019 and cost assumptions for capacity deployed in 2019 and not covered by real project cost data. On the other hand, CTI uses a national and regional weighted average, calculated based on real world project data, that tracks the deployment of renewable energy in the country. These data are then used to calculate the LCOE of solar and wind at locations near the coal plants using appropriate capacity factors given by the said locations. The individual LCOE points are thus for theoretical projects, not for projects that were actually built in 2019. Renewable energy projects do not get built necessarily where resources are the best, this being a necessary but insufficient condition, but where resources are good, the price of grid connection is reasonable, where the permitting procedure is fast and where existing infrastructure allows for the construction (e.g. roads for transporting 3-5 MW wind turbines). In the end, some sites even if they have great resources might not be suitable for the construction of renewables due to the other criteria not being fulfilled. I speculate that in the case of coal plants, the locations near them are very constraining for renewable energy development due to the grid being used to the maximum to evacuate the electricity from coal plants and additional grid reinforcements make renewable energy projects too expensive.

12 *Type II. See Footnote 6 for more information.*

13 *The exception to this would be if a grid has an extreme capacity factor that would warrant the selection of an atypical turbine type for the country. This is unlikely given our conservative use of the 20th percentile in a grid connectible region that already ignores many locations.*

14 *The global wind atlas has 250m grid spacing.*

Operating costs of coal

The operating cost of coal power can be categorised two ways.
Firstly, the short-run marginal cost (SRMC) of a coal unit includes fuel, carbon (where applicable) and variable O&M (VOM) cost. Fuel costs include the cost of buying, transporting, and preparing the coal. There are different types of coal which vary in cost depending on the energy content. The transportation costs depend on whether the coal is imported from the seaborne market or purchased domestically from a nearby mine. 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. The short-run operating cost tends to impact dispatch decisions in liberalised markets where units enter competitive markets for the right to sell power to consumers. Liberalised markets operate in the following way:

1. The grid operator forecasts power demand ahead of time.
2. 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.
3. The grid operator starts purchasing the power offered by the lowest bid operators until they add up to the required power in the forecast. This is called the uniform clearing price.
4. The grid operator pays all suppliers the same uniform clearing price regardless of what they bid. In regulated markets the way coal plants are dispatched varies depending on market structures.

Secondly, the LRMC includes SRMC plus fixed O&M (FOM) and any capital additions from meeting environmental regulations. 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, as well as installing and operating control technologies to meet regulations. While the SRMC governs dispatch decisions, the LRMC impacts the bottom-line.

Operating cashflows of coal

Revenues from in-market (i.e. wholesale power markets) and out-of-market (i.e. ancillary and balancing services and capacity markets) sources minus the LRMC.

Appendix 3 – Modelling 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 include:

- Coal 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 unit's utilisation.
- Coal-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 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 units based on 2019 statistics. We do not try and model the impact to coal from a system perspective, nor attempt to model the change to a plant's generation over time.
- We assume that coal-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 coal plants.
- We do not adjust efficiency for atmospheric conditions. 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 coal 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, especially for lignite units. 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.
- LCOE analysis is a limited metric and does not consider revenues from generation and the system value of wind and solar.[15] While the limitations of using generic LCOE analysis for understanding the economics of power generation have been well documented, it does provide a simple proxy for when new investments in coal power no longer make economic sense and when investors and policymakers should plan and implement a coal power phase-out.
- We recognize that other renewable options for power generation may be appropriate for some regions, onshore wind, offshore wind and utility-scale solar-PV have been chosen for ease of comparability and simplicity.

15 https://www.iea.org/publications/freepublications/publication/NextGenerationWindandSolarPower.pdf

Appendix 4 – Future modelling revisions and maintenance

To the best of our knowledge this is the first time anyone has attempted global coverage of coal power at asset-level. While every effort was made to model capacity as comprehensively as possible, data and model anomalies are an inevitable result of the scale and scope of this project. Over the next year, we aim to incorporate the following:

US model:
- Revised Fixed and Variable O&M based on Form 1 from the Federal Energy Regulatory Commission.[16]
- Include ongoing maintenance capex as part of the forward-looking cost based on the EIA's National Energy Modelling System.[17]
- Update combustion efficiency based on the EIA's Form 923 data.[18]
- Explore developing a methodology for those regulated coal units that self-commit.[19]

India model:
- Incorporate daily generation data from the NPP.[20]

Developed a project finance model for every planned and under-construction coal plant. The purpose of these models will be to illustrate how, under different scenarios, a coal plant project could become unviable over its lifetime. In the absence of publicly available information, we intend to develop breakeven scenarios to understand how key variables, such as electricity tariff, coal price or capacity factor, could compromise project viability. Project finance models of under-construction and planned capacity
Incorporate carbon capture and storage generation data in the IEA's Sustainable Development Scenario.[21]

Many parameters and assumptions are subject to constant change. This includes a variety of policy, economic and technological assumptions. As a result, the assumptions used in our models will be updated on a quarterly basis.

16 https://www.ferc.gov/docs-filing/forms/form-1/viewer-instruct.asp
17 https://www.eia.gov/analysis/studies/powerplants/generationcost/
18 https://www.eia.gov/electricity/data/eia923/
19 https://www.sierraclub.org/sites/www.sierraclub.org/files/Other%20Peoples%20Money%20Non-Economic%20Dispatch%20Paper%20Oct%202019.pdf
20 https://npp.gov.in/dgrReports
21 If you are aware of other revisions we should make, please contact us at coalportal@carbontracker.org

Appendix 5 – Market definitions

Deregulated markets. Subject to a competitive wholesale power market where generation activities are completely separated from the rest of the value chain.

Semi-regulated markets. Partially subject to a competitive wholesale power market where generation activities are partially separated from the rest of the value chain.

Regulated markets. Not subject to the competitive wholesale power market where generation activities are integrated into the rest of the value chain under the ownership of a vertically integrated utility.

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