TransitionZero

Coal Asset Transition Tool

Model Documentation

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About TransitionZero

We are a climate analytics not-for-profit established in 2020 with the mission to accelerate climate action by using data to support planning decisions in electricity and heavy industry. Our data is used by developers, financiers, planners and think tanks. We are entirely grant-funded by the Quadrature Climate Foundation, European Climate Foundation, Generation Investment Management, Google.org and Bloomberg Philanthropies.

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Contents

Introduction

There is a growing urgency to reduce coal-fired power generation in order to limit climate change to 1.5°C. For example, the Glasgow Climate Pact references accelerating efforts towards the phase-down of unabated (i.e., unequipped with carbon, capture, use and storage - CCUS) coal power.[1] Based on TransitionZero's analysis, aligning global coal generation with a 1.5°C goal would require closing or repurposing nearly 3,000 coal units between now and 2030.[2] This urgency has resulted in a number of initiatives to finance the retirement and replacement of coal plants.[3]

There are multiple factors which should be considered when evaluating a coal plant for early retirement, such as financial value, carbon emissions and associated costs, and environmental impacts. However, these variables are difficult to obtain at the unit and plant level, and when they are available, they are often held in disjointed databases and presented in different formats, making them nearly impossible to combine. This makes it difficult for stakeholders to screen for one or multiple of these criteria depending on their unique circumstances. With this in mind, TransitionZero developed a Coal Asset Transition (CAT) tool to allow high-level screening of coal plants. CAT provides users with key data points required to identify and rank coal plants for replacement by comparing and contrasting one or multiple criteria. These criteria include metrics representing the following Sustainable Development Goals (SDGs): SDG 3, SDG 6, SDG 7, SDG 8 and SDG 13.

Numerous industry groups, environmental organisations, and government agencies have published estimates on operating costs, air, water and carbon impacts of coal-fired plants.[4] However, these metrics are often presented in different databases and with different units that make it difficult to evaluate these negative externalities alongside operating cost to get a holistic view of the true cost of operating a plant. CAT benefits from TransitionZero's ability to estimate coal plant production and emissions in regions where data is publicly unavailable.[5] With this information, CAT has financialised the social cost of carbon, water stress, and air pollution on a $/MWh basis so that each metric can be combined with operating cost in a modular way. This allows the user to develop their own "operating cost" of the plant which can then be utilised as an input into a broader phaseout model.

1 UNFCCC (2021).
2 TransitionZero (2021).
3 Climate Investment Funds (2021).
4 See the Appendix for more information.
5 TransitionZero (2021).

Table 1. Variables calculated within CAT and relevant SDGs.

Relevant SDG	CAT Metric
SDG 3 (Good health and well-being)	Social cost of local air pollution ($/MWh)
	Social cost of total air pollution ($/MWh)
SDG 6 (Clean water and sanitation)	Social cost of water stress ($/MWh)
SDG 7 (Affordable and clean energy)	Estimated PPA price ($/MWh)
	Remaining asset life
	Cost of early retirement/Buy-out value ($)
	Potential CO2 savings from early retirement (tCO2)
	Value of carbon offset from early retirement ($)
	Reserve margin of grid (%)
	Operating cost ($/MWh)
	Short term profitability ($/MWh)
	Long term profitability ($/MWh)
	LCOE of clean replacement ($/MWh)
	LCOE of clean replacement + storage ($/MWh)
	Switch to base gas carbon cost ($/tCO2)
SDG 8 (Decent work and economic growth)	Jobs losses from closures
	Jobs added from replacement renewables
SDG 13 (Climate action)	Climate externality cost ($/MWh)

Source: TransitionZero

CAT metrics represent a 3-year average to ensure that temporary market trends do not influence long-term phaseout planning. CAT will be updated every 6 months. Along with this methodology document, an Excel data download and interactive screening tool will be made available. There are numerous other variables that could be included in CAT. We welcome recommendations from all stakeholders on how to expand to make the model more robust and impactful.

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Methodology

CAT presents plant operating cost, financial and jobs impact data points, as well as the social cost of select environmental externalities. With these metrics, users are able to obtain a holistic view of the costs of plant operation. The goal of presenting each variable in this modular fashion is so that users are able to understand and apply one or all variables for unique screening applications. Coal-fired power units are sourced from Global Energy Monitor's Global Coal Plant Tracker (GCPT).[6] The variables included in CAT represent monthly values averaged over the past 3-years.

SDG 3: Healthy lives and wellbeing

SDG 3 of the 2030 Agenda for Sustainable Development is to ensure healthy lives and promote well-being for all at all ages, and reduce the number of deaths and illnesses from hazardous chemicals and pollution.[7] Coal power is responsible for both mortality and morbidity via air pollution.

While direct pollutants, such as sulfur dioxide (SO_2) and nitrogen oxides (NO_x), have deleterious health impacts, particulate matter with a diameter less than 2.5 microns ($PM_{2.5}$) are particularly harmful because they are small enough to penetrate the lungs and enter the bloodstream, and also to penetrate the blood-brain barrier. As a result, $PM_{2.5}$ is associated with cardiovascular damage, and more recently, has been linked to nervous system damage. While research into the impact of $PM_{2.5}$ is ongoing, it is clear that a cost-benefit analysis of power plants should incorporate the known externalities.

SO_2 and NO_x also have negative health impacts, but we only model their impact via their conversion to $PM_{2.5}$ in the atmosphere. There are two reasons for this decision. Firstly, the direct impacts of SO_2 and NO_x on mortality rates are second order compared to those from $PM_{2.5}$.[8] Secondly, adding up the impacts based on separate studies of each pollutant raises the risk of double counting. This is because the pollutants are highly correlated and so the costs attributed to each often proxy for the costs of the others.

Our approach also ignores morbidity costs, such as lost days of work, childhood asthma, etc. The reason for this is again two-fold. Firstly, morbidity impacts are second order to mortality impacts in value terms. Secondly, modelling morbidity at a granular level requires far more assumptions and data requirements that we do not have at the current time. This is something we may build out the model to incorporate in the future.

To the extent that local and national governments operate in the interests of their citizens, the costs of negative health effects raise the risk of a coal plant being shut down. This can inform investors about the risk profiles of both individual plants and

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6 Global Energy Monitor (2021).

7 UN Department of Economic and Social Affairs and Sustainable Development (2021)

8 IEA (2016).

companies. Most governments try to estimate similar numbers to this as an input to inform policy. Since such cost-benefit analyses are often not publicly available, CAT may fill a gap in informing stakeholders about what governments are thinking in terms of future policy implementations.

The methodology used for estimating the mortality impacts of $PM_{2.5}$ can roughly be broken down as follows:

1. Calculate $PM_{2.5}$ inhalation attributable to each plant for the given model year. Both primary and secondary $PM_{2.5}$ converted from SO_2 and NO_x are included. A study published by researchers at Harvard concludes that simple models can capture most of the variance in inhalation rates found by complicated atmospheric models.[9] About 90% of variance, as measured by R^2, is captured by models using regressions with just 4 distance thresholds: “High risk” - 100 km, “Medium risk” - 500 km, “Medium-low risk - 1,000 km, “Low risk” - 3,300 km. As a result of this study, we can calculate the proportion of $PM_{2.5}$ mass released at the flue stack that is eventually inhaled with the following equation:

$$PM_{2.5}^{iFR} = \sum_{A_i} \alpha P_i + \epsilon$$

Where:
- $Ai = Intake\ area\ (outlined\ by\ severity\ of\ risk\ above)$
- $P_i = Population\ within\ intake\ area$
- $\alpha = Percentage\ inhaled\ by\ an\ average\ population\ member\ within\ intake\ area$
- $\epsilon = Error$

We back out the implied increase in air concentration levels using the following formula for the intake fraction (iFR):

$$iFR = \frac{\sum_{n=1}^{n} P_i C_i BR}{Q}$$

Where:
- $BR = Breathing\ rate\left(\frac{m^3}{d}\right)$
- $P_i = Population\ in\ area\ i$
- $C_i = Incremental\ pollution\ concentration\ in\ area\ i$
- $Q = Emissionrate\left(\frac{g}{s}\right)$

Current particulate matter assumptions are based on the emissions intensities utilised in the Air Pollution Impact Model for Electricity Supply (AIRPOLIM-ES) published by the New Climate Institute, originally published by GAINS (calculated for Parry et al. 2014). Emissions intensities are broken out at the country level by pollutant type ($PM_{2.5}$, NO_x, SO_2) and control type (controlled v.

9 Harvard School of Public Health (2006)

uncontrolled). This means that the variability in air pollution externalities is driven by pollutant type, control type, as well as population density surrounding the plant.

2. Use an empirically calibrated relationship between $PM_{2.5}$ inhalation and mortality for the diseases most associated with $PM_{2.5}$ concentrations to calculate the number of deaths attributable to each plant in relevant subregions around the plant. Such a relationship is known as the concentration response function (CRF) and is assumed linear. This means that if 10% of a population die from a given disease and the CRF is 10% for a 10 mg/m3 increase in $PM_{2.5}$, a 20 mg/m3 increase in concentration of $PM_{2.5}$ in an area will increase the percentage of people who die from that disease in the area to 10 * 1.1 = 12.1%). We rely on the 2019 global burden of disease data from the World Health Organisation (WHO), which has country level mortality rates for the 4 main air pollution related diseases we model (lung cancer, chronic obstructive pulmonary disease, ischemic heart disease, and stroke).[10]

3. Calculate the social cost of these deaths based on the statistical values of life. The "statistical value of life" is an economic metric representing the local trade off between fatality risk and money. This process involves calculating different statistical values of life for each country in the calculation region following IMF adjustment formulas.[11] If any costs from pollution are projected into the future, they will be discounted using the Social Time Preference Rate (STPR) defined by the UK's HM Treasury.[12]

$$SVL_{Country} = SVL_{OECD}\left(\frac{Income_{Country}}{Income_{OECD}}\right)^{\epsilon}$$

   Where:
   - $SVL_{Country} = Statistical\ value\ of\ life\ within\ model\ country$
   - $SVL_{OECD} = Average\ statistical\ value\ of\ life\ within\ OECD\ countries$
   - $\epsilon = SVL{:}\ Income\ ratio$

   We use an SVL_{OECD} of $3 million based on a comprehensive meta-analysis of studies on the statistical value of life performed by OECD after accounting for CPI inflation defined for the OECD.[13]

Once mortality rates and the social costs of these deaths have been calculated using the above methodology, we then divide this cost by the total generation in the time period of interest to convert the cost to a $/MWh. We identify the total air pollution externality cost, as well as the local (in-country) air pollution externality cost, understanding that governments may not be interested in calculating the negative impacts of their power generation on neighbouring countries.

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10 WHO (2019)

11 IMF (2014)

12 HM Treasury (2020)

13 OECD (2012)

SDG 6: Clean water and sanitation

SDG 6 of the 2030 Agenda for Sustainable Development is to ensure availability and sustainable management of water and sanitation for all.[14] Coal plants use water to cool, process, clean and burn coal. This use can come at the expense of other uses. Coal plants require large amounts of water for operation. Water is necessary to cool off process equipment, for use as a heat sink for the thermodynamic cycles of the power plant, and to a lesser extent, for coal-pre-treatment and pollution control. There are numerous cases of coal plants being mothballed due to a lack of water. One drastic occurrence of this was in India in 2016, when during an extreme drought, 14 TWh (around the total annual thermal generation of Sri Lanka), was unable to operate due to a lack of water.[15]

To quantify water stress, we apply a methodology developed by Michael Ridley and David Boland, which builds on Bloomberg's Water Risk Valuation Tool.[16] The model aims to quantify the value of water to various sectors outside of power generation by calculating a "shadow price", or the Total Economic Value of Water (TEV). The TEV serves to capture the increasing cost of water as supply decreases and demand increases. The main inputs into this shadow price calculation are from the Baseline Water Stress (BWS) from WRI's Aqueduct database[17], population data[18] and the value of disability adjusted life (DALY). DALY is a World Health Organization (WHO) metric which represents the loss of the equivalent of one year of full health.

$$TEV = Agricultural\ value * Domestic\ value + Human\ health\ impact + Environmental\ impact$$

Where:

- $Agricultural\ value = \frac{2W}{5}$
- $Domestic\ value = P\left(\frac{4}{5}(W + 1)\right)$
- $Human\ health\ impact = PD\left(2 * 10^{-8} * W^2 + 10^{-8} * W + 10^{-7}\right)$
- $Environmental\ impact = P\left(\frac{W}{10}\right) * \left(0.031 * W^2 + 0.015 * W\right)$
- $W = WRI\ Aqueduct\ Baseline\ Water\ Stress\ (BWS)\ score$
- $P = Population\ weight$
- $D = Value\ of\ disability\ adjusted\ life\ year\ (DALY)$

The TEV then serves as input to calculate the total negative externalities associated with water stress for a particular plant. The following water usage rates are assumed based on cooling type and technology utilised.[19] These water rates represent only *net* water usage of the plant. Once-through water usage captures only the net water extraction, and recirculating cooling captures only the evaporative loss. Because net

14 UN Department of Economic and Social Affairs and Sustainable Development (2021)
15 WRI (2021)
16 Ridley and Boland (2018)
17 Aqueduct Water Risk Atlas (2019)
18 UN Department of Economic and Social Affairs and Sustainable Development (2021)
19 World Nuclear Association (2020)

water loss volumes are utilized, the social cost of water stress presented in CAT is a conservative estimate. While net water usage may be low, there may be circumstances in regions with high water stress in which there isn't enough water to meet throughput requirements for cooling, which this version of CAT does not capture.

Table 2. Net water use by cooling technology type

Technology & Cooling Type	Net water Usage (L/kWh)
Coal, once-through, subcritical	0.52
Coal, once-through, supercritical	0.47
Coal, recirculating, subcritical	1.75
Coal, recirculating, supercritical	1.96

Source: World Nuclear Association (2020)

Given the above assumptions, the amount of water used at each power plant is estimated from the amount of power generated over the time period of analysis. From there, the financialisation of water stress per unit of generation is calculated with the following equation:

$$Water\ stress\ externalities\ (\$/MWh)\ =\ \frac{Total\ water\ usage * TEV}{Generation\ (MWh)}$$

While WRI's Aqueduct tool is relatively comprehensive, there are still a few gaps in BWS scores for certain geographies. In situations where there is no available Aqueduct data outlining water stress, we assign a value of zero for the water externality cost in order to avoid overestimating the negative externalities associated with water stress at the plant level. This will be refined in future renditions of CAT. Additionally, we plan to expand water stress to include gross water usage to more accurately depict the risk water stress poses to plant operation.

SDG 7: Affordable and clean energy

SDG 7 of the 2030 Agenda for Sustainable Development is to ensure access to affordable, reliable, sustainable and modern energy for all.[20] The following CAT metrics relate to this SDG:

Cost of early retirement/Buy-out value

Assessing the cost of early retirement for coal-fired power plants typically requires the quantification of the financial value of the plant, which will form the basis for negotiations of the price of a buy-out. This is typically done from two differing perspectives: (1) assessing the remaining investment value of the asset using un-recuperated capital expenditure and (2) assessing the value of future revenue streams.

Assessment of the remaining investment value, sometimes referred to as the book value of the plant, may undervalue the asset because it disregards any potential for additional return on investment. The assumption of a full buy-out of the future revenue streams, in this case the remaining power purchase agreement (PPA) values, may likely result in over-compensation for coal plant owners, potentially leaving consumers to foot the bill if public financing is being used.

The need to reconcile both the cost and value perspectives of power plants underpins why the estimation of the cost of early retirement is a challenge, with various nuances. TransitionZero's methodology of estimating the cost of early retirement is underpinned by the following equation:

$$Cost\ of\ early\ retirement = Year\ of\ early\ retirement * Annual\ generation * (PPA\ tariff - Fuel\ cost - Carbon\ cost)$$

Where:

- Year of early retirement = Number of years of buy-out in an early retirement scenario
- PPA tariff = Estimated Current tariff price per unit of electricity generated ($/MWh)
- Fuel cost = Three year average fuel cost ($/MWh)
- Carbon cost = Three year average carbon cost ($/MWh)

The principle underpinning our methodology is that the cost of early retirement needs to be acceptable for all stakeholders involved. Power plant owners need to be fairly compensated for lost profits, while financiers cannot be expected to overpay for the asset.

Thus, TransitionZero's methodology builds on top of a cost-based approach, adding a buffer of profit margin on the coal plant. The cost of early retirement estimated will then cover the CAPEX, OPEX, and an acceptable profit margin of the plant. Fuel cost

20 UN Department of Economic and Social Affairs and Sustainable Development (2021)

is removed from the calculation as it is assumed that the unused coal will be sold on the international market, and thus does not need to be bought out. Carbon costs are also removed from the costs of the coal plants as such costs will not be incurred once the plant is shut down.

The buyout process with differ from country to country based on unique regional regulations and other nuances. Please see the Appendix for country specific methodologies.

An important caveat to note here is that while we present data for early retirement of captive plants, these calculations do not factor into our overall cost of retirement estimates. This is due to:

- Some captive plants are located in areas that are underserved by the national grid. Thus, they may not be able to access grid electricity if they are shut down.
- Some captive plants are integrated into industrial processes, which makes it challenging to redesign and rework processes and industrial sites when retiring these assets.
- The financial mechanisms and incentives underpinning retirement of captive are poorly understood.

PPA tariff

Power plants are typically financed via power purchase agreement (PPA), this forms the basis of mapping future revenue streams of coal plants, as well as in the calculation of the profitability of said plants. A PPA is a contractual agreement between a buyer and seller. They come together and agree to buy and sell an amount of power which is or will be generated by the generation asset. For the purpose of this tool, we refer to PPA prices in more general terms to refer to agreements to sell electricity at predetermined prices.

In most markets, PPAs are considered commercially sensitive and are not publicly available. The case is even more severe in regulated electricity markets, where PPA terms are held in close confidentiality.

As seen from Table 4, readily available PPA data at the asset-level is not common in Asia. Even if they are available, data collection is likely to be challenging due to the diversity of source material (particularly for media articles). To address these challenges, we have come up with an in-house methodology to incorporate PPAs into the CAT tool. These methodologies are very market-specific and seek to incorporate as much market sensitivity as possible.

Table 3: PPA data availability in select regions

Country	PPA data availability
China	Poor - PPAs details are seldom publicly available.
India	Decent - PPAs details are sometimes reported by regulators or on media articles. Data collection is likely to be a challenge.
Japan	Poor - PPAs details are seldom publicly available.
South Korea	Decent - PPAs details are sometimes reported by regulators or on media articles. Data collection is likely to be a challenge.
Indonesia	Decent - PPAs details are sometimes reported by regulators or on media articles, however, such data points may be unreliable and are hard to verify.
Vietnam	Poor - PPAs details are seldom publicly available.
Philippines	Good – The Energy Regulatory Commission (ERC) typically report on their downstream PSAs (Power Supply Agreements).

Source: TransitionZero

Please see the Appendix for country specific PPA methodology and details.

Early retirement

There is no universally accepted definition of what early retirement means. For the purpose of this exercise, TransitionZero has come up with an early retirement schedule.

For assets with remaining life less than 10 years, “early retirement” will mean buy-out of the remaining life of the asset for immediate shutdown. "Early retirement" for assets with remaining life greater than 10 years will see a maximum buy-out of 10 years of coal generation.

Remaining asset life

The remaining asset life represents the number of years, from the current year, that the plant would be expected to operate based on the operational lifetime of the plant under business-as-usual conditions. This value is utilized in the calculation of carbon savings from an early shut down, as well as in the buyout value of the plant. In both calculations it is assumed that the early retirement of the plant would take place immediately, in the current year.

$$Remaining\ asset\ life = Operation\ years - (Start\ year - Current\ year)$$

Potential CO2 savings from early retirement

As carbon offsets become a more prominent tool for companies and countries alike to meet net-zero goals, quantifying the value of carbon is increasingly important. CAT quantifies the potential carbon emissions savings from an early retirement as follows:

$$Carbon\ savings\ (tCO2) = Pei * Annual\ generation\ (MWh) * Years\ of\ early\ retirement$$

Where:

- P_{ei} = Plant emissions intensity (tCO2/MWh)

Value of carbon offset from early retirement

The value of the above “eliminated” emissions is then quantified, based on an assumed value of carbon.

$$Value\ of\ CO2\ savings\ (\$) = Carbon\ savings\ (tCO2) * Assumed\ carbon\ offset\ value\ (\$/tCO2)$$

An assumed carbon offset value of $10/tCO2 is utilised for the calculations in the CAT data download and dashboard. However, the user can input their own carbon offset value into the CAT UI to calculate the value of these offset carbon emissions based on their own assumptions.

Reserve margin

Coal plant retirement planning cannot be done in silos and must be viewed through a lens of overall grid stability and reliability. For example, it will make more sense to retire a coal plant in an area where there is overcapacity, vis-a-vis an area where the supply barely meets power demand. As such, we attempt to provide a layer of additional insights on the state of grid infrastructure in the region using reserve margin as a proxy.

Please see the Appendix for country specific reserve margin methodology and details.

Operating cost

The operating cost of the plant represents the dollar amount required to produce one unit of electricity.

$$Operating\ cost\ (\$/MWh) = Fuel\ price\ (\$/MWh) + Carbon\ cost\ (\$/MWh) + VOM\ (\$/MWh) + FOM\ (\$/MWh)$$

Where:

- VOM = Variable O&M costs
- FOM = Fixed O&M costs

Fuel cost and carbon costs have been converted from $/t and $/tCO2 to $/MWh respectively, for the purpose of integration into the operating cost calculation. VOM and FOM costs are derived from 2020 WEO Plant cost assumptions. We assume FOM is equal to 90% of the VOM cost, unless more granular information is available on a country-by-country basis.

For countries which rely on coal imports, a weighted fuel price is calculated based on the countries of origin for 90% of all coal imports using data from UN Comtrade and ICE for the corresponding price indices. For countries where coal is mined locally, pit-mouth pricing is used from local databases. Prices account for fuel quality, import taxes, transportation costs, etc. Where transport and/or tax information is unavailable, we assume a $5/t transport cost and 20% import tax.

Long term profitability

The long-term profitability of the plant represents the profits of the plant based on operating cost of the plant. While this is largely driven by operating costs, the tariff price received by the plant ultimately dictates the profits.

$$Long\ term\ profitability\ \ (\$/MWh) = Tariff\ price(\$/MWh) - \ Operating\ cost\ \ (\$/MWh)$$

LCOE of clean replacement

The levelized cost of electricity (LCOE) of clean replacement – meaning utility scale solar PV or onshore wind- represents the price on a MWh basis to recoup project costs and achieve a required hurdle rate on investment.

LCOE of clean replacement + storage

The LCOE of clean replacement + storage is the same as the above, but also accounts for the cost of storage associated with the installed clean replacement technology.

Switch to base gas carbon cost

The switch to base gas carbon cost represents the carbon price on a $/tCO2 basis to trigger a fuel switch decision from coal generation at existing coal plants to gas generation at new-build gas plants. This value is an output of TransitionZero's Coal to Clean Carbon Price Index (C3PI).

Energy subsidies

For many countries, energy subsidies are an extremely influential factor in the power sector. Where applicable, TransitionZero has accounted for energy subsidies on a country by country basis. Please see the Appendix for country specific energy subsidy methodology and details.

SDG 8: Decent work and economic growth

SDG 8 of the 2030 Agenda for Sustainable Development is to promote inclusive and sustainable economic growth, full and productive employment and decent work for all.[21] In order to meet the temperature goals of the Paris Agreement, closure of coal-fired power plants is required. These closures however, will inevitably have an adverse effect on the communities reliant on those plants for employment and economic activity. In order to ensure a just transition toward renewable energy, it is important to understand the job losses that will result from coal plant closures.

There are various ways to quantify jobs tied to an industry, which are often broken down into three major categories:

- Direct jobs - Those jobs directly tied to the sector in question
- Indirect jobs - Those jobs tied to supporting and supplying the sector in question
- Induced jobs - Those jobs created when employees of the above two categories spend income in the economy.

This analysis will focus only on the direct job impact. This evaluation also estimates the actual number of jobs created/associated with a specific technology, rather than job-years, which can often cause confusion and create opaqueness around the actual number of jobs associated with a project. The direct jobs impact is calculated both for the job loss associated with a coal plant closure, as well as for the jobs created by replacing that generation with new renewables generation.

$$Direct\ jobs\ impact\ =\ Estimated\ jobs/MW\ *\ Plant\ capacity\ (MW)$$

For each country, a literature review is conducted to determine the appropriate value to use for the number of jobs per MW of installed coal capacity. Oftentimes, the original data is conveyed in job-years. In these cases, the following steps are taken to convert the metric to number of jobs created:

- Convert the job-years metric to job-years on an annual basis, if not already presented that way. For example, 700,000 job-years created over a 10-year horizon is the equivalent of 70,000 jobs over a 1-year horizon.
- Calculate the number of direct jobs associated with a project, assuming 50% of the jobs created are direct jobs, with indirect and induced jobs each compromising another 25% of total job creation.[22]
- Calculate the number of jobs associated with installed capacity as outlined by the literature reviews.

The transition away from coal should not only focus on the jobs lost from plant closures, but also those created by the construction and operating of replacement clean technologies. The required renewables capacity required to replace an operating coal plant is calculated as follows:

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21 UN Department of Economic and Social Affairs and Sustainable Development (2021)

22 Global Green Growth Institute (2020)

$$Replacement\ RE\ capacity\ (MW) = \frac{Annual\ coal\ generation\ (MWh)}{8760 * RE\ capacity\ factor\ (\%)}$$

A literature review is then conducted similar to the process outlined above to determine how many jobs are associated with each MW installed for both solar and onshore wind. Thus, CAT captures both the jobs that will inevitably be lost with each coal plant closure, but also those that will be created with the construction of replacement clean technologies, giving a holistic view of the jobs impact associated with coal phaseout. With proper retraining programs, previous coal plant workers can benefit from the transition to clean power generation. Such programs will be vital to ensuring a just transition as economies move away from fossil fuels and toward renewable power generation.

SDG 13: Climate action

SDG 13 of the 2030 Agenda for Sustainable Development is to take urgent action to combat climate change and its impacts.[23] To quantify a carbon price consistent with the 1.5°C goal, we use the assumptions outlined in the IEA's 2021 World Energy Outlook (WEO) Net Zero Emissions by 2050 scenario.[24] WEO assumes a carbon price of $130/tCO2 for advanced economies, $90/tCO2 for major emerging economies and $15/t for other emerging economies.[25] In order to capture the externalised "climate cost" associated with each asset, we calculate the difference between the WEO outlined net zero carbon pricing and any carbon pricing already in place in order to avoid double counting. These prices are converted to $/MWh based on the assumptions detailed in the Appendix.

[23] UN Department of Economic and Social Affairs and Sustainable Development (2021)

[24] IEA (2021)

[25] Advanced economies are those part of the Organisation for Economic Cooperation and Development (OECD), while advanced economies include China, Russia, Brazil and South Africa.

Multiple unique criteria

These key variables have been presented separately so that they can then be used as inputs into a user-defined phaseout model. This allows stakeholders to include, exclude, and weight any combination of the outlined variables in a way that is best suited for user-defined phaseout criteria and constraints.

Limitations

CAT should not be seen as a 'turnkey' solution, but rather a publicly available tool for stakeholders and decision-makers to undergo an initial screening of plants which show potential to be replaced based on one or more criteria. CAT metrics represent a 3-year average to ensure that temporary market trends do not influence long-term phaseout planning. CAT will be updated every 6 months. We believe the CAT Tool has two main limitations: it includes only limited criteria on grid stability and does not account for regional indirect employment impacts. These limitations are discussed below and in the future iterations section.

Power cannot be stored in the grid, so the amount of electricity fed in must always be the same as the amount of electricity fed out. This means production and consumption must always be balanced. This equilibrium ensures the secure and stable operation of the grid at a constant frequency. If unforeseen fluctuations arise, the operators in the grid control rooms use a reserve that power plants keep available and that can be retrieved as required. The power plants either increase or decrease their power to compensate for any missing or excess electrical energy. Closing assets requires careful consideration as they have the potential to destabilise the grid. Based on the current version of CAT, grid stability assessments should be conducted separately in collaboration with grid operators and resource planners. In future iterations, we intend to incorporate grid stability assessments through Future Energy Outlook (FEO), an upcoming open-source systems planning model that we are developing.

Closing and repurposing coal has a number of impacts such as regional employment and economic issues. This is particularly the case for coal mining and power assets, which tend to be outside of urban areas for geological and planning reasons. If not properly addressed, these issues risk marginalising communities and stifling the transition to a zero-carbon economy. While this iteration of CAT includes an estimate of the *direct* jobs impact for each asset, it does not include implications from coal mine closures that may result from plant closures. We hope to expand on this data point in the future.

Future iterations

We openly acknowledge there will be additional iterations we have overlooked in the initial iteration of the CAT Tool. The first iteration of CAT includes only Indonesia, with future plans to expand to China, India, Japan, Korea, Philippines and Vietnam. We welcome recommendations from third parties on how to expand to make the model more robust and impactful. Below is a non-exhaustive list of the data points which would allow the CAT Tool to advance beyond being a high-level screening tool. This list identifies those data points already included in CAT, as well as those not yet included but would add value to future iterations. This list is based on our understanding of publicly available datasets and the first iteration of the CAT Tool.

Table 4. Data points that should be included in any comprehensive phaseout model

Category	Data Variable	Publicly available
Inventory	Location	GCPT, GEM
	Capacity	GCPT, GEM
	Age	GCPT, GEM
	Boiler technology	GCPT, GEM
	Start date	GCPT, GEM
Operational	Efficiency	CAT, TransitionZero
	Generation	CAT, TransitionZero
	Capacity factor	CAT, TransitionZero
Financial	Electricity prices	CAT, TransitionZero
	Coal prices	CAT, TransitionZero
	Initial investment	CAT, TransitionZero
	Pollution control costs	CAT, TransitionZero
	Undepreciated value	CAT, TransitionZero
	Replacement cost	CAT, TransitionZero
	Gross profitability	CAT, TransitionZero
	Financing	CAT, TransitionZero
	Tax income	No
Contractual	Ownership	GCPT, GEM
	Off taker	No

	Off take contract terms	No
	Pricing	CAT, TransitionZero
	Fuel supply contracts	No
Infrastructure	Transport infrastructure	No
	T&D infrastructure	No
	Coal mining operations	No
Environmental	Carbon intensity	CAT, TransitionZero
	Water use	CAT, TransitionZero
	Air pollution	CAT, TransitionZero
Regulatory	Electricity market structure	CAT, TransitionZero
Economic	Jobs impact	CAT, TransitionZero

Source: TransitionZero analysis

As detailed above, one obvious weakness of the first iteration of the CAT Tool is the inability to understand system costs and impacts associated with replacing coal plants. We are developing an energy system model called Future Energy Outlook (FEO). FEO intends to provide critical insights on energy markets, policy, and the future of the global energy system. FEO will be based on objective data, transparent assumptions, open-source modelling, and dispassionate analysis. FEO will use a scenario-based approach and rigorous scientific methods to illustrate how the energy system might evolve during the coming decades and how it is affected by key variables, chief among them the policies adopted by governments around the world. Crucially, FEO will be guided by three high-level principles:

- Transparent model methodology, assumptions, and code base available for users to replicate
- Informed by a geographically diverse and internationally regarded steering group to ensure local buy-in
- Based on least cost principles with no policy adjustment, so this pathway can clarify the cost of decarbonisation

FEO will improve the CAT Tool by providing insights into full system cost and additional phaseout criteria at the plant level.

Conclusion

We developed the CAT Tool to help decision-makers screen coal plants for replacement and/or phaseout in order to meet the 1.5°C goal. The CAT Tool aims to be a flexible tool to allow decision-makers to screen for one or more of the criteria, including financial value, energy affordability, as well as air, water and climate externalities and jobs impact. Our hope is CAT will be a useful resource for both stakeholders and decision-makers to ensure coal plants are replaced in the most economically efficient and socially just way possible.

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Appendix 1. Indonesia-specific model adjustments

PPA tariff

For Perusahaan Listrik Negara (PLN), the Indonesian state-owned utility, PPA prices refer to the implied costs of generation when a PLN-owned assets send electricity to the grid.

In the case of Indonesia, we have split the market based on five types of plants: (1) PLN[1]-owned plants (mine-mouth); (2) PLN-owned plants; (3) independent power provider (IPP) owned plants (mine-mouth); (4) IPP-owned plants and (5) captive plants, where power plants are owned by industries for self-generation. Table 5 below lists the methodology of how PPA prices are estimated.

Table 5: Our methodology on estimating PPA tariffs in Indonesia

	Methodology	PPA price	Operation years
PLN-owned plants	Reported PPA price	Based on the reported PPA price in media reports etc	Pre-2020: 30 years Post-2020: 25 years
	Unknown PPA price (Coal fired power plant)	Based on PLN reported cost of production, adjusted by year of operations and regional scaling	
	Unknown PPA price (Mine-Mouth)	Based on PLN reported cost of production, adjusted by year of operations and regional scaling Further aligned to other mine-mouth plants	Pre-2020: 35 years Post-2020: 30 years
IPP-owned plants	Reported PPA price	Based on the reported PPA price in media reports etc	Pre-2020: 30 years Post-2020: 25 years
	Unknown PPA price (Coal fired power plant)	Discounted off regional BPP*, adjusted by year of operations and known price in the region	
	Unknown PPA price (Mine-Mouth)	Discounted off regional BPP, adjusted by year of operations and known price in the region Further aligned to other mine-mouth plants	Pre-2020: 35 years Post-2020: 30 years
Captive plants	Unknown PPA price	Discounted off regional BPP, adjusted by year of operations and known price in the region	Pre-2020: 30 years Post-2020: 25 years

Source: TransitionZero
Note: BPP refers to the average regional cost of production.

A key principle underpinning our methodology is the equal treatment between PLN-owned and IPP-owned assets when estimating the cost of retirement. This is because both PLN and IPPs will need to recoup their investments equally. However, there is a differentiation made in the treatment of PPAs, therefore the cost of early coal retirement is already cheaper for PLN-owned plants than for a like-for-like comparison.

Reserve margin

In the case of Indonesia, estimates of reserve margin at both the regional and sub-regional grid levels are retrieved from the Rencana Usaha Penyediaan Tenaga Listrik (RUPTL 2021-2030), or the national utility, PLN's 10-year business plan. Table 6 below shows the regional grids in Indonesia, as well as their associated sub-regional groupings.

Table 6. Regional grids and sub-regional breakdowns

Regional grids	Sub-regional breakdowns
Java-Bali	Central Java
	West Java
	East Java
	Banten
	Bali
Sumatra	Bangka-Belitung
	Bengkulu
	Aceh
	North Sumatra
	Lampung
	West Sumatra
	Riau
	Jambi
Kalimantan	South Kalimantan
	West Kalimantan
	Central Kalimantan
	East Kalimantan
Sulbagsel	South Sulawesi
	Southeast Sulawesi
	Central Sulawesi

Sulbagut	North Sulawesi
	Gorontalo
Maluku	Maluku
North Maluku	North Maluku
Papua	Papua
West Nusa Tenggara	West Nusa Tenggara

Source: TransitionZero
Note: In the remote islands, including parts of Sulawesi, Maluku, Papua and Nusa Tenggara, reserve margins are estimates, due to the presence of many small islands and separate island mini-grids.

Energy subsidies

A discussion on Indonesia’s power sector cannot be complete without covering energy subsidies. Coal prices to power plants are currently capped at $70/ton for power plants. This implies a coal subsidy that is the difference between the prevailing market price of coal and the subsidised rate.

TransitionZero estimated the cost of fuel subsidies using an in-house methodology. The coal subsidy per ton of coal is the difference betwxeen the prevailing reference market price (HBA price) released by ESDM, and the fuel price for each plant. We adjusted the HBA price from the 6322kcal/kg to an average 4200kcal/kg, to account for quality differences between the benchmark coal quality and the energy content of coal consumed in Indonesian power plants. To get the total subsidy, we estimated the annual coal consumption based on the 4200kcal/kg energy content of coal and the average thermal efficiency of 35% across Indonesia’s coal fleet. The total coal subsidy will then be the coal subsidy per ton multiplied by the total consumption by the coal fleet.

Appendix 2. Philippine-specific model adjustments

The CAT Philippines dataset excludes metrics on air pollution and water stress, and instead focuses on the financial and operational metrics of plants, which are based on collected generation and pricing data from power supply agreements. A tab containing metrics per PSA collected is provided in the downloadable dataset.

Buyout estimates

The Philippines has a fully liberalised electricity sector. Therefore, adjustments in the methodology have to be made to account for the unique aspects of the market. The most critical aspect to consider is the variety and structure of PPA – also known as power supply agreements (PSAs) in the Philippines – that are tied to one asset. We use the terms PSA and PPAs interchangeably.

Coal plant operators are free to contract their power to different off-takers, including registered distribution utilities (DU), electric cooperatives (EC), and retail market players. Under this regime, coal assets have multiple PSAs/PPAs with differing durations, counterparties, pricing, and pricing structures.

Due to varying maturities of existing PPA/PSAs, the coal plant cannot retire until the last PPA/PSA has expired. Thus, the buy-out value for coal plants in the Philippines should be estimated on a contract-by-contract basis, rather than on the asset level. We have introduced the cost of **immediate buy-out** to estimate the costs of buying out all of the remaining PPA/PSAs for immediate plant closure. We assume no PPA/PSA extension is available for renewal and that this capacity is no longer able to be contracted out once the contract expires.

Given that coal plants would operate until early 2050 following existing PSAs, we also provide a cost of **early retirement** metric that is the summation of buying out each existing PSA tied to a particular asset, with the maximum buyout year for a PSA capped at 5 years.

Another crucial aspect of the Philippine market that affects buyout estimates is the existence of the Wholesale Electricity Spot Market (WESM). Because power sold on the spot market does not have a minimum offtake volume and is subject to the plant's standing in the merit order and the power demand in the market, it is difficult to value in relation to buyout, as historical performance is likely to be a poor indicator of the future and forecasting spot prices far out into the future cannot be done robustly. To avoid introducing bias and skewing representation, we have disregarded potential spot market income streams in the asset valuation. However, we understand that valuing the potential spot market profits will need to be accounted for in actual coal retirement and refinancing valuation exercises and negotiations. We disclose the percentage contracted in the CAT dataset, as an indicator of the plant's exposure to the WESM or retail market.

PPA tariff
Data for generation, duration, and tariffs for PSAs are available through Energy Regulatory Commission (ERC) filings and Power Supply Procurement Plans (PSPPs) submitted to the DOE by DUs and ECs. We have collected monthly generation charge, monthly generation, PPA/PSA start date, and PPA/PSA end date for the full analysis period (Jan 2020 to December 2023) from publicly available documents.

While this has resulted in a robust dataset that covers 209 PSAs, there are partial or full gaps for some assets included in the database. Table 7 presents the methodology for how we treat such data gaps in our estimation of average PPA/PSAs prices and average annual generation, which are used to estimate the buyout cost and other operational costs available on the CAT tool.

Table 7: Methodology for estimating PSA-based generation and price in the Philippines

	PPA/PSA (Full)	PPA/PSA (Partial)	TZ methodology
Feature	Full price, monthly generation data points for PPA/PSA, running through the full analysis period of January 2020 to December 2023	Some price and generation data for the period of January 2020 to December 2023 is available	No data points on price, generation data points for PPA/PSA, for the period from Jan 2020 to Apr 2023
Treatment	Not applicable	To prevent subjective analyst judgment from skewing the value of the asset, we do not attempt to fill in gaps for partially available datasets as the analysis period covers a particularly volatile time that saw power sector players responding differently. If either generation or price was available, the missing data point was calculated.	**Price**: average of other PPA/PSAs from the same plant **Generation**: Minimum generation listed in the PPA/PSA, when available. When unavailable, use typical capacity factors for contract terms (baseload: 80%; mid-merit: 45%, peaking: 20%) Since the tariff may deviate significantly from the “estimated tariff” at the point of ERC approval, the PPA/PSA tariff is estimated using the average of all other PPA/PSAs signed under the same coal plant.
Coverage	76 PPA/PSAs	108 PPA/PSAs	16 PPA/PSAs*

Source: TransitionZero
*9 PPA/PSAs having no reported price/generation, despite available reporting by the DU/EC, therefore, we have assumed that these PPA/PSAs have not yet entered into force.

We understand the lack of available data may undervalue or overvalue the PPA/PSA on an average basis. Additional generation and price data may become available in the future and affect the estimates for each asset. For transparency, we disclose the methodology used to estimate each PSA in the dataset.