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Financing Indonesia's coal phase-out: A just and accelerated retirement pathway to net-zero

Imprint

Financing Indonesia's coal phase-out: A just and accelerated retirement pathway to net-zero

Center for Global Sustainability,
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Key Message

Indonesia is one of the world's largest coal producers and consumers, and has signaled its openness to adopting a more ambitious net-zero target and a 2040s coal phaseout with international support. Such additional support could address the broader socio-economic implications of achieving the 1.5°C-compatible coal-to-clean power transition and ensure the accelerated transition is also carried out in a just and equitable way.

Although various financing mechanisms are under discussion, identifying the most beneficial strategies will require refinement of how to evaluate the just transition financing needs, what elements should be considered, and how to effectively allocate the limited resources to achieve the best outcome in the near term that can also set a robust pathway towards the long-term goals.

This research uses a structured methodology to develop a feasible plan and associated financing needs for retiring Indonesia's coal-fired power plant fleet in support of national 2050 net-zero emissions and the global 1.5ºC target. Using the best data available, we conduct a comprehensive and systematic assessment to understand the magnitude and distribution of the benefits and costs of the accelerated, just coal transition in Indonesia.

Our key findings include:

1. The pathways in line with 2050 net-zero emissions and global 1.5°C show Indonesia's coal power generation decreases by 11% in 2030, by over 90% in 2040, and is completely phased out by 2045.
2. Immediate retirement of 4.5 GW of "low-hanging fruit" plants which are older, dirtier, and more inefficient can reduce emissions by 28.8 $MtCO_2$ per year and help improve air quality, public health, water security, etc.
3. According to the detailed retirement schedule presented here, 18 plants (9.2 GW, 8 PLN & 10 IPP plants) retire by 2030, 39 plants (21.7 GW, 18 PLN & 21 IPP plants) retire in 2031–2040, and the remaining 15 plants (12.5 GW, 5 PLN & 10 IPP plants) continue to operate beyond 2040 at a low utilization level and retire before 2045.
4. The accelerated coal phaseout is feasible and beneficial from the economic and social perspectives – the positive and broadly shared benefits from avoided coal power subsidies and health impacts are 2-4 times larger than the costs on stranded assets, decommissioning, employment transition, and state coal revenue losses.
5. Retirement costs are estimated to be 4.6 billion USD through 2030 and 27.5 billion USD through 2050. About 2/3 of the costs are associated with IPP plants and 1/3 with PLN plants. The large upfront costs for retirement necessitate substantial international support, despite the larger benefits gained in the long run.
6. Cancelling pipeline projects under PPA or construction may save up to 18.7 billion USD that can be alternatively invested in renewable energy.
7. The accelerated coal phaseout can reduce cumulative CO_2 by 341 $MtCO_2$ through 2030 and 2,297 $MtCO_2$ through 2050, making the retirement costs equivalent to approximately \$12-13/tCO_2 removed.
8. As coal power is replaced by renewable energy, primarily solar, to meet increasing demand, the investment required to scale up renewables and transmission is estimated at 1.2 trillion USD through 2050, where international financing can help fill in the gap.

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1. Introduction

About 66% of Indonesia's electricity is currently generated from coal-fired power plants (CFPPs). The country has about 86 CFPPs[1] currently in operation with a total installed capacity of 40.2 GW, placing it in the 7th position globally[2]. With such a huge proportion in existence, coal power plants contributed to a staggering 79% of the country's power sector CO_2 emissions in 2019[3], accounting for more than a quarter of the country's total CO_2 emissions[4]. At the same time, with the rapidly falling cost of renewables, coal power is losing its economic competitiveness in Indonesia. Building new renewable energy (especially utility-scale solar PV) is expected to be cheaper than building new coal-fired power plants by 2023 or even sooner (BNEF and IESR 2021).

Because of the increasing competitiveness of renewable energy and the likelihood of strong climate policies such as carbon pricing in the future, coal will need to be phased out in Indonesia to achieve economic, health, and climate goals. As a first step, the national government has pledged to reduce its reliance on coal and encourage a larger share of renewables in the generation mix. Through its updated Nationally Determined Contribution (NDC), the government aims at curbing the country's greenhouse gas (GHG) emissions by 29% (voluntarily) or 41% (with international support) relative to the business as usual (BAU) by 2030 (Republic of Indonesia 2021). As a start, the Ministry of Energy and Mineral Resources (MEMR) has shared its near-term target to retire 9.2 GW of Indonesia's coal-fired power plants by 2030 (Katadata 2021). Aligned to the target is a plan proposed by PLN to completely phase out coal-fired power plants by 2056, and to prohibit new coal projects beyond 2023, with the exception of projects that are already under construction or reaching their financial close. Nevertheless, the existing government reduction target and utiity phaseout plan are still not ambitious enough to contribute to the orchestrated effort to keep the global average temperature below 1.5°C. More CFPPs will still come online since they have been financially closed and contracted from last year. Within the planned-to-be-retired CFPPs list, only 40% of then will be replaced by renewables (Katadata 2021). An accelerated coal-to-clean power transition is urgently needed to maintain the target temperature within reach—and will importantly also deliver enhanced net benefits such as economic growth and improved health as well in Indonesia.

Enhanced actions are still possible, and important recent policy discussions in Indonesia indicate interest in exploring these directions. Indonesia has indicated openness to the possibility of adopting a more ambitious 2050 net-zero target and accelerating coal phaseout with international support. At COP 26, the minister of MEMR signed the Coal to Clean Power Transition statement, agreeing to the coal phaseout acceleration into the 2040s, conditional on receiving additional international financial and technical assistance (UNCC 2021). Broader socio-economic implications must be considered from complying with the 1.5°C-compatible coal-to-clean power transition, including stranded assets, job losses, investments to scale up renewables, etc. Therefore, additional support has been requested to address the broader impacts and ensure the accelerated transition is also carried out in a just and equitable way.

Different financing mechanisms have been discussed and explored in other countries' contexts, for example, South Africa's Just Energy Transition Partnership (JETP). Forged during COP 26, the United Kingdom, the United States, France, Germany and the European Union have collectively pledged to provide an initial amount of $8.5 billion to assist South Africa's long-term and just transition process (African Development Bank 2022). The partnership is expected to reduce coal reliance in South Africa's power system, whilst at the same time promoting development of new sectors such as green hydrogen and electric vehicles. Furthermore, the partnership is envisaged to shape the investment and funding landscape needed in South Africa's energy

[1] Data source: Ember, Electricity Data Explorer, Accessed July 2022
[2] Data source: Global Energy Monitor, Global Coal Plant Tracker, January 2022; Authors' adjustments
[3] Data source: IEA country data - Indonesia, 2020; Authors' calculation
[4] Ibid.

transition and to centre its resources towards wider socio-economic development, protecting workers and communities. Another financing mechanism, Energy Transition Mechanism (ETM), was also recently initiated by Asian Development Bank (ADB) and jointly launched with Indonesia and the Philippines as key partners during COP26 (Asian Development Bank 2021). The partnership is specifically addressed to aid the coal to clean energy switch in Southeast Asia, with pilot projects expected to be held in Indonesia, the Philippines and Vietnam. The first seed of financing amounts up to $25 million has been announced by Japan's Ministry of Finance. The ETM will oversee the financing of just energy transition, accelerated coal phase out and renewable energy developments through a scalable and collaborative initiative, encouraging investments from public and private sectors. Despite all of these promising initiatives, it still remains unclear how to evaluate just transition financing needs, what elements should be considered, and how to allocate the financing assistance among different domestic and international stakeholders.

To inform ongoing policy discussions on financing the just transition, this paper uses a structured methodology to develop a feasible plan and associated financing needs for retiring Indonesia's coal-fired power plant fleet in support of national 2050 net-zero emissions and the global 1.5°C target. Using the best data available, we conduct a comprehensive and systematic assessment to understand the magnitude and distribution of the benefits and costs of the accelerated, just coal transition in Indonesia. Specifically, the analysis is conducted using a three-step approach (Figure 1). First, we develop the pathways for national 2050 net-zero emissions using a global integrated assessment model (the Global Change Analysis Model, GCAM[5]). Second, we structure detailed plant-by-plant retirement pathways based on fulfilling multiple national priorities simultaneously and that also achieve the 2050 net-zero target. These pathways are generated by combining the top-down net-zero pathway and bottom-up plant-level assessments in light of national priorities such as air quality, health, economic benefits, and more. Individual coal plants are identified for retirement at specific times based on their technical, economic, and environmental performance. Third, we estimate the magnitude of financing needs by systematically assessing the benefits and costs of implementing a just, rapid coal-to-clean energy transition. A framework is developed to evaluate the economic, social, and environmental outcomes that are directly and indirectly related to the accelerated phase out of coal-fired power plants. The framework also assesses the impacted shareholders, including coal-related industry, government, and the general public, in the process.

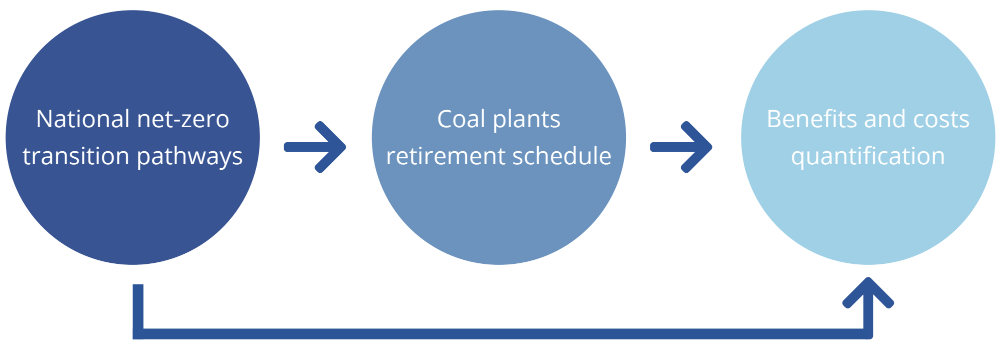


Figure 1. Research Overview

[5] http://jgcri.github.io/gcam-doc/index.html

2. Developing The Plant-By-Plant Coal Retirement Pathways

As of May 2022, Indonesia has 86 CFPPs in operation with a total installed capacity of 40.2 GW. Among these, 26 plants (12.5 GW) are owned by PLN, 32 plants (18.5 GW) are owned by Independent Power Producer (IPP), and the remaining 23% capacity are off-grid captive plants (Figure 2a). Indonesia's coal plants are relatively young, with 75% built after 2005. Moreover, total capacity is still expected to increase with additional projects in the pipeline. 19 new projects (10.8 GW, 11 new plants, and 8 expansion projects) are under construction, three projects (1.5 GW) have signed power purchase agreements (PPA), and 11 projects (8.7 GW) are at early development stages. The majority of PLN and IPP plants are located in Java-Bali and Sumatra (Figure 2b).

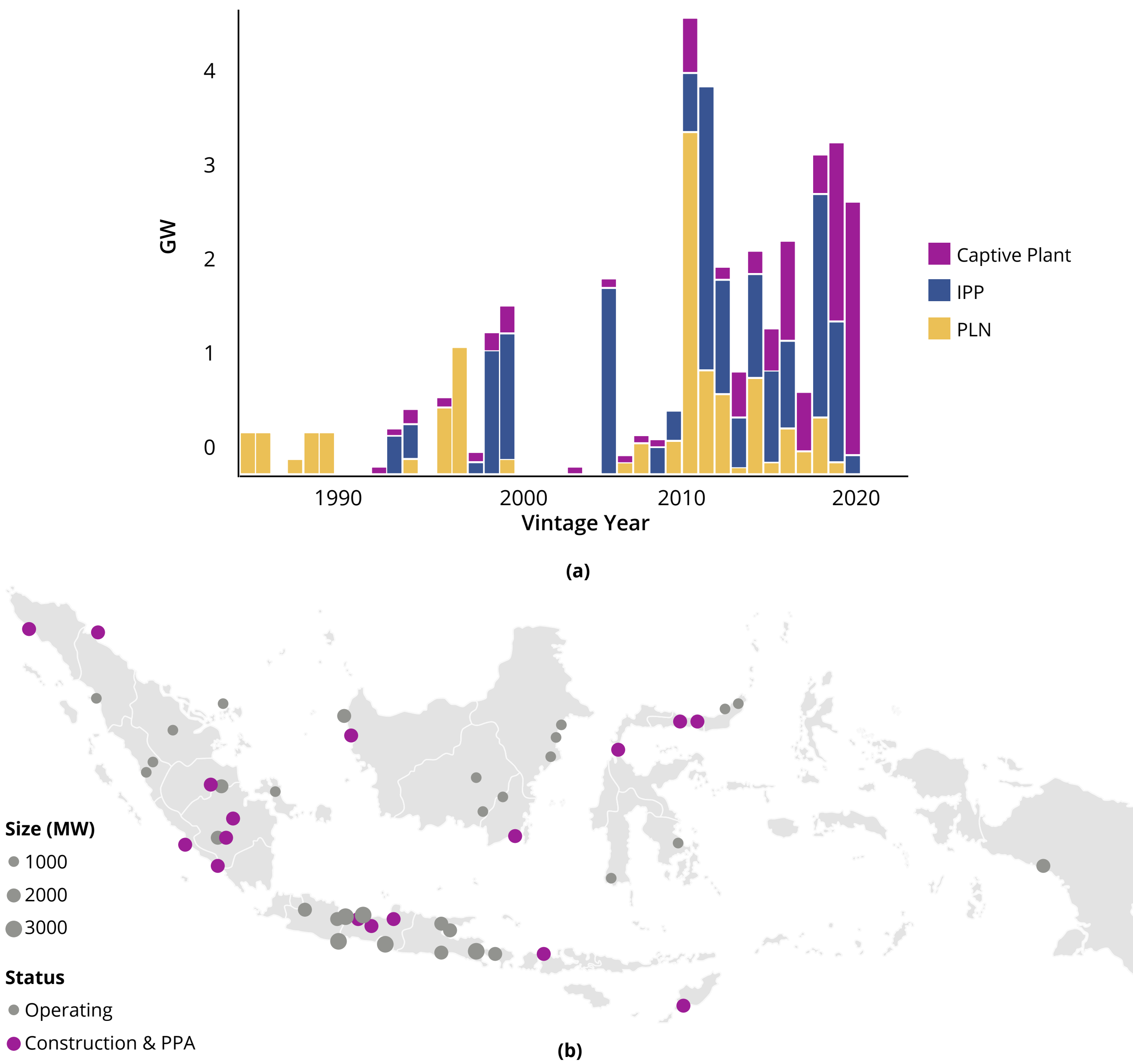


Figure 2. Indonesia's existing and under construction (PPA) coal-fired power plants: (a) total capacity by vintage year and by owner; and (b) plant location.[6]

[6] Data source: Global Coal Plant Tracker, January 2022; Authors' adjustments

Using a global integrated assessment model, the Global Change Analysis Model (GCAM), we develop the national pathways in line with achieving net-zero CO_2 emissions by 2050 in Indonesia and keeping the temperature change within 1.5°C globally (see Technical Appendix for more details). Overall, emissions reductions are achieved through electrification and low-carbon fuel switching in end-use sectors (industry, buildings[7], and transport) and rapid decarbonization of power generation (Figure 3a). Specifically, unabated coal power generation declines by 11% in 2030, by over 90% in 2040, and is phased out by 2045. Coal is replaced by renewable energy, primarily solar, to meet increasing demand through 2050 (Figure 3a).

By 2030, canceling the 11 (8.7 GW) projects that have not started construction/PPA and retiring 8 GW that reaches the 30-year lifetime, coal power emissions increase will be limited to 216 $MtCO_2e$ from 184 $MtCO_2$. The developed pathway requires closing plants before the designed 30-year lifetime; continued coal builds will further shorten it.

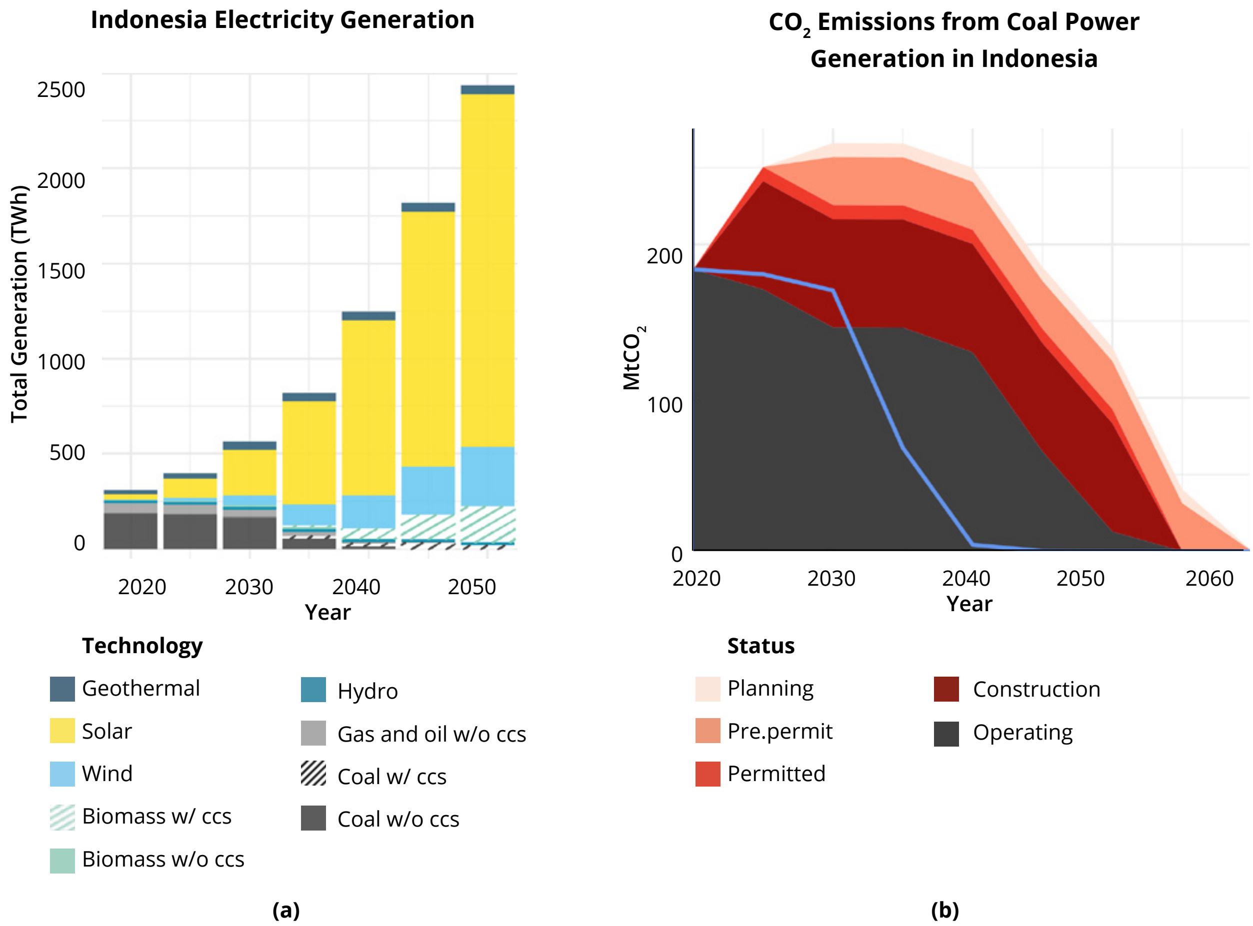


Figure 3. Pathway compatible with 2050 net-zero emissons for Indonesia: (a) electricity generation by technology, and (b) coal power generation CO_2 emissions from GCAM (line) in comparison with the trajectory for operating, under construction, permitted, planned, coal power capacity over time (solid areas).

[7] Including residential and commerical buildings

Our analysis focuses on the 72 non-captive CFPPs (43.4 GW) that are currently operating, under construction, or have signed the power purchase agreement (PPA). Among these, 15.7 GW is owned by PLN, the state-owned power company, and 27.7 GW belongs to independent power producers (IPP), who sign long-term contracts with PLN for the power generated. The list does not include coal power plants with a capacity below 30 MW. Most of the newer, larger, and more efficient plants are owned by IPP, and most of the new capacity is developed by IPP (Figure S1 in Technical Appendix). In particular, IPP owns the majority of the capacity built within the past decade, while the oldest plants (30~40 years) belong to PLN. IPP owns the majority of the units larger than 600 MW. IPP also owns the majority of the units with super-and ultrasuper-critical technologies. Moreover, out of the 12.3 GW of new capacity to be added, 9.2 GW is developed by IPP, including all three new projects with PPA contract. The 11 new projects at early development stages should focus on cancellation instead of transition support.

By assessing the technical, economic, and environmental performance of individual coal plants, we assign a combined score between zero and one to each plant as the retirement priority ranking. A lower score closer to zero indicates an earlier retirement, and a higher score closer to one indicates the plant is the last to retire. In particular, technical attributes are assessed based on the plants' age, size, and combustion technology; economic performance is based on the gross profits per capacity unit; and environmental impacts are based on CO_2 emission rate, local air quality and health impact, and water security (see Technical Appendix for more details).

Moreover, a small set of plants are identified as low-hanging fruit (LHF) plants due to their poor performance across all technical, economic, and environmental dimensions (see Technical Appendix for more details). These plants (12 coal plants, 30 units, a total of 4.5 GW) can be retired quickly in the near term, i.e. between 2022 and 2023, to help improve air quality, public health, and water security (Table 1). LHF plants are mostly located in Java-Bali, Sumatra and Kalimantan (Figure 4). Some plants are retired due to their aging conditions as they reach the end of their economic lifetime, such as Banten Suralaya and PLN Paiton in the Java-Madura-Bali system, Bukit Asam Muara Enim for the Sumatra system and Asam-asam for the Kalimantan system. Some have notorious track records. Having been constructed close to residential areas, Cilacap Sumber and Ombilin power plants have been subjected to complaints for closure from the residents due to the Fly Ash Bottom Ash (FABA), knowingly causing respiratory problems.

Table 1. Overview of the LHF plants

Subnational	Plant	Capacity (MW)	Year	Retirement	Technology
Bangka-Belitung	Bangka Baru power station	60	2014	2023	subcritical
Banten	Banten Suralaya power station	1600	1984	2023	subcritical
Banten	Merak power station	120	2014	2023	subcritical
Central Java	Cilacap Sumber power station	600	2006	2023	subcritical
East Java	PLN Paiton power station	800	1994	2023	subcritical
Lampung	Tarahan power station	100	2007	2023	subcritical
South Kalimantan	Asam-Asam power station	260	2000	2022	subcritical
South Kalimantan	Tabalong power station	200	2019	2023	subcritical
South Kalimantan	Tabalong Wisesa power station	60	2013	2023	cfb[8]
South Sumatra	Bukit Asam Muara Enim power station	260	1987	2023	subcritical
West Java	Cikarang Babelan power station	280	2017	2023	subcritical
West Sumatra	Ombilin power station	200	1996	2023	subcritical

[8] Circulised Fluidised Bed, one type of boiler used in the subcritical steam-cycle technology

Figure 4. Location of the LHF plants

By combining the national pathway and plant retirement ranking, we then develop the plant-by-plant retirement schedule. First, the national coal power generation constraint from GCAM is met by retiring coal plants one by one starting from the lowest to highest combined score at today's utilization levels. We then apply a minimum guaranteed lifetime (20 years) to plants that are retired before that age, except for the low-hanging fruit plants. Retirement schedule for PLN and IPP plants is shown in Table 2. With the minimum lifetime, some plants are now retired later than needed to meet the national coal generation constraints from GCAM, average utilization will decline from 5,935 hours today to 4,807 hours by 2030, and 1,090 hours by 2040.

Table 2. PLN and IPP coal plants retirement schedule

# of Plants, GW	PLN Retirement	IPP Retirement	Total Retirement
2022-2030	8 plants, 5.0 GW	10 plants, 4.2 GW	18 plants, 9.2 GW
2031-2040	18 plants, 7.6 GW	21 plants, 14.1 GW	39 plants, 21.7 GW
2041-2045	5 plants, 3.1 GW	10 plants, 9.4 GW	15 plants, 12.5 GW

The retirement of CFPPs is not concentrated in a particular region, but well-balanced across different power systems in Indonesia (Figure 5 & 6). Increases in CFPP capacity are observed in the Java-Bali and Sumatra systems due to new projects already under construction. However, both regions are expected to face serious overcapacity issue if the expansion plan under current PLN's electricity supply business plan (Rencana Umum Penyediaan Tenaga Listrik, RUPTL) RUTPL is followed. For example, the Java-Bali power system, where there is an additonal 13 GW of coal capacity which can introduce serious overcapacity issue, increasing the system reserve margin up to 60% (Bisnis 2021). Therefore, canceling projects that have not started construction or signed the PPAs, plus the retirement of older CFPPs can help address the overcapacity issue. The Kalimantan, Sulawesi, Maluku, and Papua systems would experience phased decline in CFPP capacity, reaching a complete phase-out between 2040-2045.

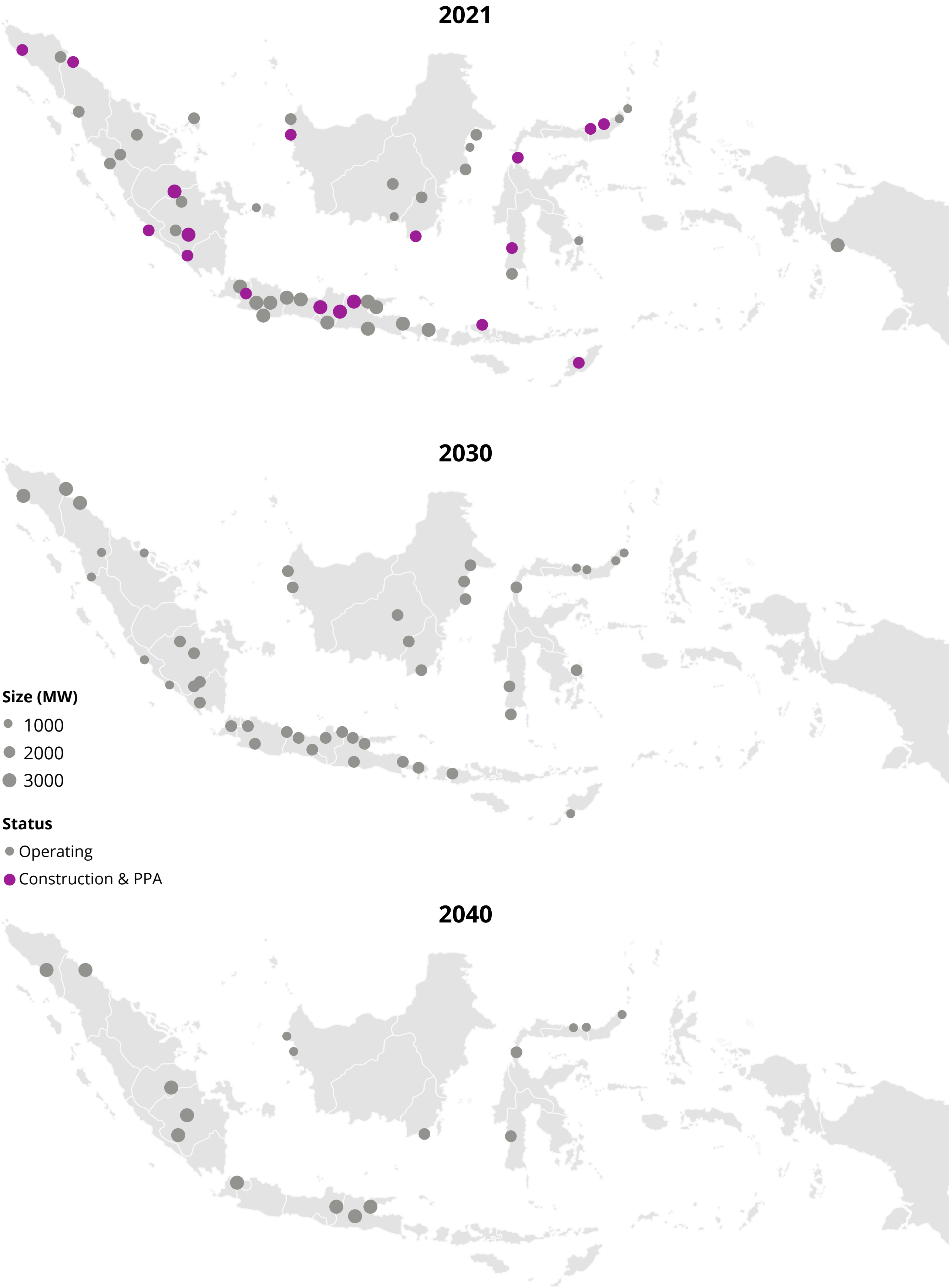


Figure 5. Location of the operating and under construction / PPA coal-fired power plants in 2021, 2030, and 2040 under the accelerated retirement plan.

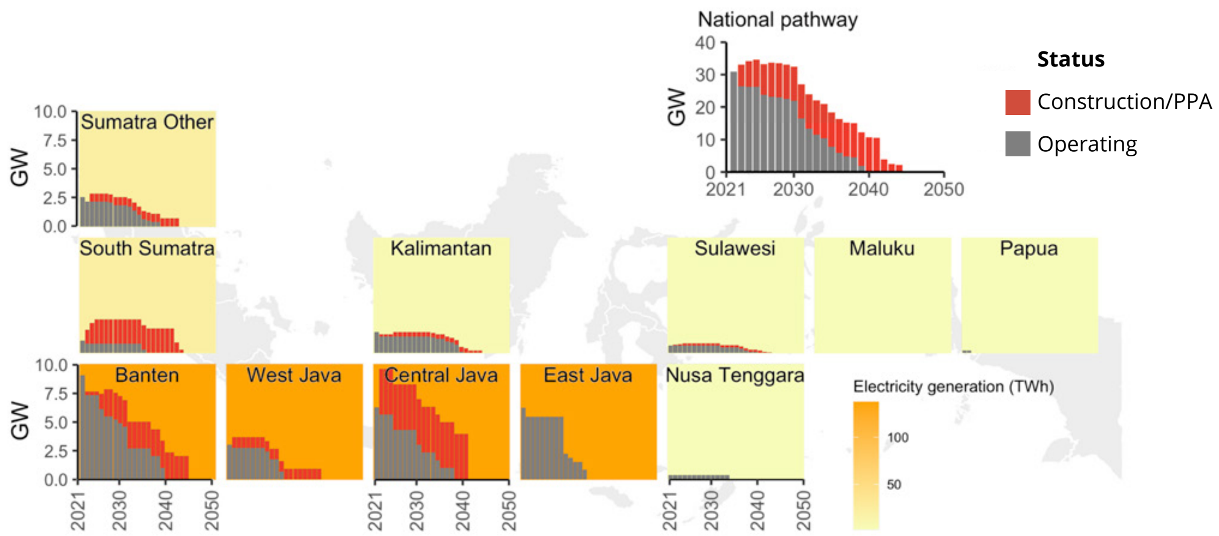


Figure 6. Coal retirement pathways by region. The bars show the total coal-fired power capacity in operation by year in each region, colored coded by projects' status today.

Retirement Plan for Selected Plants

In addition to the low hanging fruit plants, as shown in Table 1, several other power plants bound for early retirement are highlighted here. These power plants are included due to their well-known controversies reported in mainstream media outlets and a few key disadvantages.

- Along with other units, Tanjung Jati B is infamously known as the third largest power plant in Indonesia, trailing behind Paiton and Suralaya. In terms of ownership, the power plant is owned by IPP. From the analysis, its 1,320 MW unit 1 & 2, which are projected to be less efficient compounded with bad economic performance, will be retired in 2026, 20 years after its Commercial Operation Date (COD).
- Another less efficient power plant on the list is Indramayu. The power plant, owned by PLN and with a total capacity of 990 MW, is projected with higher environmental impacts, if it does not go into retirement in 2030/2031, having served for 20 years. The impacts have actually been subjected to complaints by the surrounding community, dominated by farmers and fishermen, due to quality degradation of their crops and reduction in the amount of caught fish (Kompas 2020).
- Similar efficiency deterioration is also expected in Paiton Baru unit 9. The unit itself has a total capacity of 660 MW with IPP ownership. It is colocated within the proximity of other units in Paiton power plant compound, which is known as the largest power plant in Southeast Asia. Apart from being less efficient, the unit is flagged with a concern of higher water risk, indicating potential problems related to water saving and quality. Therefore, the retirement is scheduled for 2035, by which time the unit will be already 23 years old.
- As in Indramayu, Cirebon 1, an IPP power plant with a total capacity of 660 MW, is also seeing higher environmental impacts. This, in addition to the pledge of one of its shareholders that indicates a move away from coal-related businesses, forms a strong motive for the unit's retirement in 2034. By then, the age of the unit will be 22 years old.
- The last unit on the list is Celukan Bawang. The power plant is located in Indonesia's tourism mecca, Bali. It is owned by IPP, has a total capacity of 381 MW, and, moreover, has been applauded to maintain Bali's grid reliable and stable (VOI 2022). Even so, the power plant has also been subjected to protests from nearby residents and fishermen for disrupting their livelihood (Mongabay 2019). The unit itself will go into retirement at the age of 20 years old in 2035.

3. Quantify Costs and Benefits of The Just Transition

We develop a comprehensive framework to assess the financing needs associated with implementing the proposed retirement pathway through a just transition. The framework (Table 3) evaluates the impacts across three dimensions - economic, social and environmental - including the benefits (e.g., air quality and public health improvements), the costs (e.g., stranded assets and decommissioning costs), and the policy and financial need to address potential negative consequences (e.g., compensation and fiscal support for coal job losses).

Moreover, the framework helps us understand how these benefits and costs are distributed among different stakeholders: the coal-related industry, the government, and the general public. The coal-related industry would bear costs such as stranded assets and decommissioning, while they would benefit from avoided air pollution retrofit costs. The government, in contrast, must consider state revenue loss, tax income loss, and fiscal support for job losses, but would gain from coal electricity subsidies that they no longer need to pay. The general public would benefit from improved air quality and health and an increase in green jobs, but there would be costs associated with job losses and CFPP support to the surrounding communities.

Due to constraints in data and time, not all of the metrics in the framework were quantified. However, we quantified the metrics that we thought were the most consequential, and assumed that the unquantified metrics are insignificant in comparison.

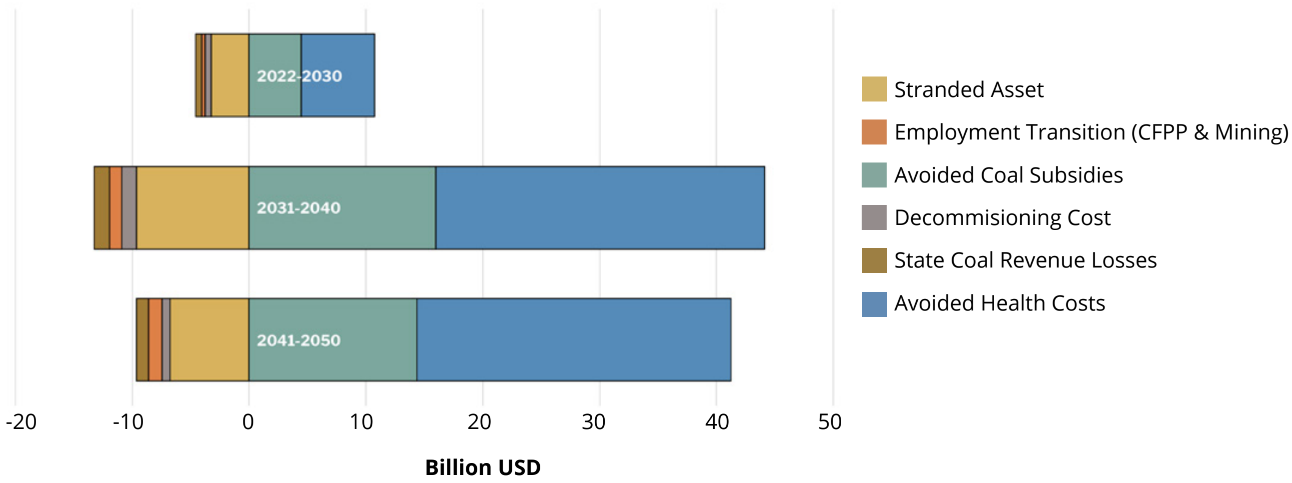
Table 3. Analytical framework of the accelerated coal power phaseout. It covers the economic, social, and environmental benefits (blue) and costs (green) or uncertain outcomes (yellow) that are either directly or indirectly from CFPP retirements for different stakeholders—the coal-related industry, government, and the public.

Economic	Social	Environment
Stranded assets for PLN	Fiscal support for job losses (CFPP and supply chain)	Avoided air pollution control retrofit cost
Decommissioning cost	Job losses compensation (CFPP and supply chain)	Reclamation cost
Avoided coal electricity subsidies	Public health benefit	Air quality improvement
Early retirement compensation for IPP	Human development	Water savings and water quality
State coal revenue losses	Green job growth	GHG emission reduction
Tax income losses	CFPP support to surrounding community	
Policy incentives for RE deployment	Job and income losses CFPP and supply chain)	
Energy access		

Coal-related Industry | Government | Public | Benefit | Cost | Uncertain Outcomes

Using the best data available, we estimate the retirement costs at $4.6 billion through 2030 and $27.5 billion through 2050, while the total savings from avoided coal power subsidies and avoided public health costs amount to $34.8 and $61.3 billion, respectively (Figure 7). The accelerated coal phaseout is feasible and beneficial from the economic and social perspectives—the avoided coal power subsidies and health costs are 2–4 times as large as the costs of stranded assets, decommissioning, employment transition, and state coal revenue losses.

The large upfront costs of retirement necessitate substantial international support, despite the larger benefits gained in the long run. Over the period 2041 to 2050, benefits are more than four times the costs, at 41.2 billion and 9.6 billion USD, respectively. The quantified benefits consist of health improvements and avoided coal subsidies. They jump in value between periods 2022-2030 and 2031-2040 and continue to increase through 2050. The quantified costs are dominated by retirement compensation, stranded assets, and state coal revenue losses, and also include decommissioning costs and employment transition. They increase from period 2022-2030 to period 2031-2040, but decrease in period 2041-2050.



Metric (million USD)	2022-2030	2031-2040	2041-2050
Stranded Asset	3,233	9,628	6,740
Decommisioning Cost	533	1,259	729
Employment Transition (CFPP & Mining)	272	1,041	1,161
State Coal Revenue Losses	542	1,363	1,012
Avoided Coal Subsidies	4,442	15,998	14,396
Avoided Health Costs	6,292	28,121	26,843

Figure 7. Benefits and costs for implementing the accelerated coal retirement plan in a just way. Benefits are shown as positive numbers and costs as negative numbers on the top bar chart; Benefits are shown in blue and costs in purple in the bottom table.

When assessing the costs relative to IPP versus PLN plants, IPP plants are associated with a larger share of the costs. About two-thirds of the costs are associated with IPP plants, with the remaining one-third attributed to PLN plants (Figure 8). For the three projects (1.5 GW) that have signed power purchase agreements (PPAs), we estimate the total retirement costs at 1.2 billion USD[9], and the total investment costs at 1.4 billion USD. Together, the implementation and retirement of these projects could cost 2.6 billion USD, and can be otherwise invested directly in renewable energy if these projects are cancelled. Similarly, the implementation and retirement of the 19 projects (10.8 GW) already under construction could cost 8.6 billion USD and 7.5 billion USD, respectively.

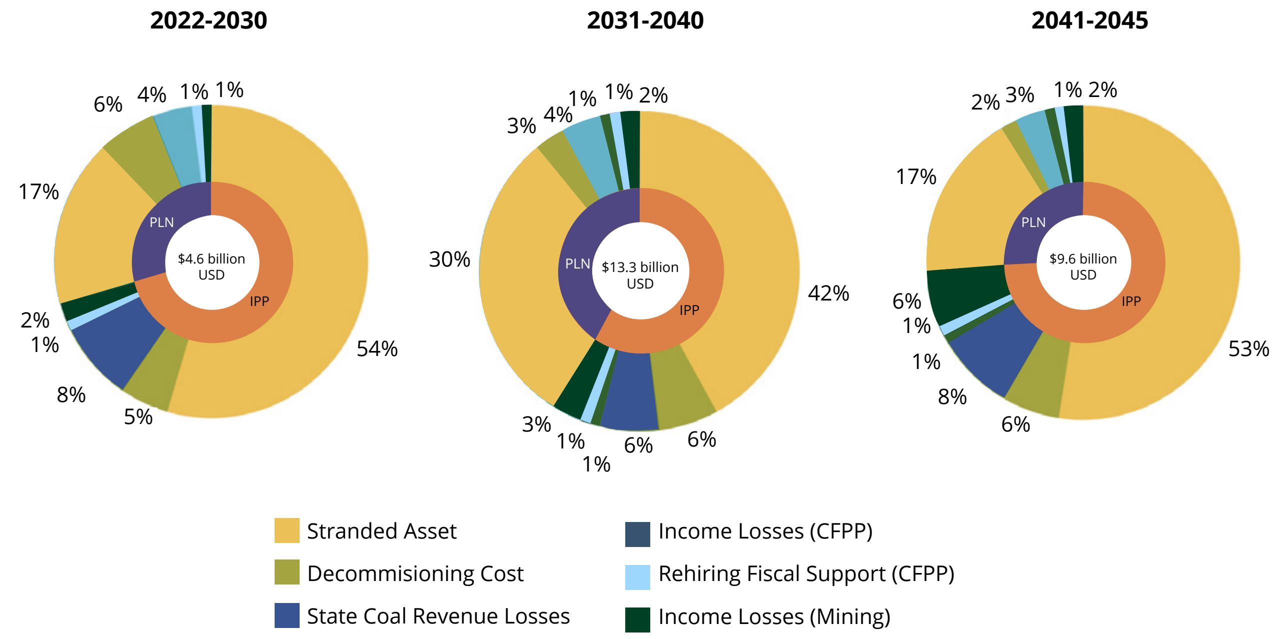


Figure 8. Costs of the accelerated coal phaseout breakdown by category and PLN vs. IPP plants in 2022-2030, 2031-2040, and 2041-2050.

We also quantify the investments necessary to facilitate the proposed retirement pathway in Indonesia. Over 1.2 trillion USD is needed to replace coal power generation with renewables and meet increasing electricity demand through 2050 (Figure 9). Renewable energy investments make up over 75% of total investments by 2050, with solar, wind and storage playing a large role consistently. Biomass becomes a more prominent player over time, as its share of renewable investments increases from less than 1% in 2030 to 5% by 2050. Meanwhile, the investment shares for geothermal power and hydro power shrink over time.

Investments in transmission and distribution and energy efficiency are also critical elements, making up 19% and almost 5% of total investments, respectively. Additionally, there is minimal investment in fossil technologies, accounting for less than 1% of total investments.

[9] It excludes the income losses for mining jobs, which is not estimated at the plant level.

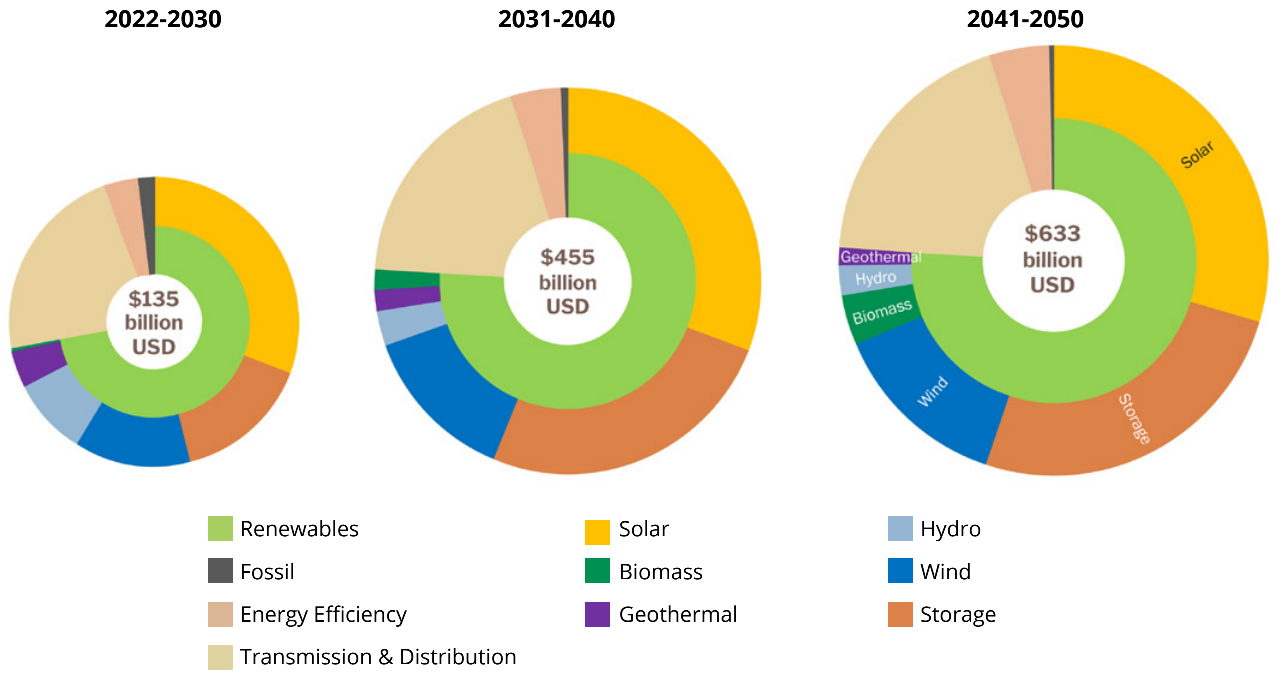


Figure 9. Power system investment by technology in 2022-2030, 2031-2040, and 2041-2050.

With huge scale of investment required for renewable energy, energy efficiency, and energy infrastructures, there is a critical need to prepare a focused strategies to attract the required investment. This is because, since 2016, investment realization for renewable energy and energy efficiency has consistently scored below the government target, averaging around 1.5-2 billion USD annually (IESR 2022b). The investment must scale up by ten times to around 15 billion USD to reach the 135 billion USD total investment by 2030. The figure is still within reach as the total energy investment (including fossil fuel) in the country has easily surpassed 35 billion USD for the last five years. Therefore, one reasonable strategy is shifting the bulk of the total energy investment into renewable and energy efficiency.

Due to its limited figures, the role of public finance could be focused on either creating an appealing investment climate for renewable energy or generating a market for renewable energy and energy efficiency for the local industries. An example is bringing back the feed-in-tariff regulation (currently in the form of presidential regulation draft) and/or executing the mandatory rooftop solar installation for public buildings. The positive investment climate brough about by these regulations might allure enough interest from private, in which the vast of investment for renewable energy and energy efficiency should come from.

4. Conclusions and Discussion

Through a plant-by-plant assessment and rooted in the national priorities of Indonesia, analysis develops a feasible and structured plan for retiring the entire coal-fired power plant fleet in Indonesia in support of national 2050 net-zero emissions and the global 1.5ºC target. Using the best data available, our analysis conducts the first systematic assessment of the just transition financing for phasing out Indonesia's coal-fired-power plants. It outlines the important elements to be considered, provides an estimate of the magnitude and distribution of the financing need, and illustrates how to idenfitying the most beneficial strategies that can effectively allocate the limited financing resources to achieve the best near- and long-term outcomes.

Key findings of the analysis are:

- The pathways in line with 2050 net-zero emissions and global 1.5°C show Indonesia's coal power generation decreases by 11% in 2030, by over 90% in 2040, and is completely phased out by 2045.
- Immediate retirement of 5 GW of "low-hanging fruit" plants which are older, dirtier, and more inefficient can reduce emissions by 28.8 $MtCO_2$ per year and help achieve other development priorities on air quality, public health, water security, etc.
- According to the detailed retirement schedule presented here, 18 plants (9.2 GW, 8 PLN & 10 IPP plants) retire by 2030, 39 plants (21.7 GW, 18 PLN & 21 IPP plants) retire in 2031–2040, and the remaining 15 plants (12.5 GW, 5 PLN & 10 IPP plants) continue to operate beyond 2040 at a low utilization level and retire before 2045.
- The accelerated coal phaseout is feasible and beneficial from the economic and social perspectives – the positive and broadly shared benefits from avoided coal power subsidies and health impacts are 2-4 times larger than the costs on stranded assets, decommissioning, employment transition, and state coal revenue losses.
- Retirement costs are estimated to be 4.6 billion USD through 2030 and 27.5 billion USD through 2050. About 2/3 of the costs are associated with IPP plants and 1/3 with PLN plants. The large upfront costs for retirement necessitate substantial international support, despite the larger benefits gained in the long run.
- Cancelling pipeline projects under PPA or construction may save up to 18.7 billion USD that can be alternatively invested in renewale energy.
- The accelerated coal phaseout can reduce cumulative CO_2 by 341 $MtCO_2$ through 2030 and 2,297 $MtCO_2$ through 2050, making the retirement costs equivalent to approximately \$12-13/tCO_2 removed.
- As coal power is replaced by renewable energy, primarily solar, to meet increasing demand, investment required to scale up renewables and transmission is estimated at 1.2 trillion USD through 2050, where international financing can help fill in the gap.

Given that the process of phasing out coal will be conducted in more than 25 years, there should be a strong and cohesive political will through the creation of no-regret policy and strong regulatory framework for phasing out CFPP. Phasing-out coal power plants would require strong push from the national government and assurance to all main stakeholders. Early this year, the government of Indonesia mentioned the need to form Presidential Regulation for phasing-out 5.5 GW coal fleet going to 2030 (detikcom 2022). While this may be sufficient in the short term, a stronger energy policy and its coherency with other relevant policies (development policy, climate policy, etc) must be established, since the process would take more than two decades and would go through multiple Presidential terms.

Currently, the parliament is planning to review the Energy Law (no. 30/2007) and the government has to update its Energy Plan (RUEN/Presidential Regulation 22/2017). The energy plan can be revisited once every five years if there is a fundamental change in the law and/or strategic environmental change, including changes in the energy planning indicators on national, regional as well as international levels (antaranews.com 2022; Warta Ekonomi 2022). Both policies could be used to strengthen the policy framework supporting the coal phase-out. Additionally, the long-term development plan 2024-2045 by the Ministry of National Development Planning (in which the process should start early next year) should also integrate the coal phase-out and align this with other development plans e.g. the industry and human resources development aspects. The latter will help ensure Indonesia reaps the socio-economic benefit and apply the just process during Indonesia's coal phase-out.

CFPP retirement pathway must be considered in the planning of the next RUPTL of PLN and other utilities. The CFPP phase-out process must not put the power system security at risk. One way to make certain of this is to assimilate the CFPP phase-out plan in the next cycle of PLN's electricity supply business plan (RUPTL). Therefore, the decommissioning of CFPP could be timed well with the replacement renewable power plants procurement process. PLN (and other utilities) could test, project the cost, and optimize the power system plan, minimizing the risk of a system failure while maintaining the overall system cost. This step will come after the policy is clear in the first place, therefore the timing window is by the end of 2022 to get the phase-out policy done.

Scaling up renewable energy and energy storage should be integrated with the CFPP retirement plan. Indonesia needs to build up a massive project pipeline and be ready to deploy renewable projects. Renewable energy in Indonesia has been slow to take off in the last five years. Investment has only been hovering around USD 1-2 billion annually, indicating a reform in renewable energy policy and regulations is critical (IESR 2022b). Stakeholders are waiting for policy (e.g. new energy and renewable energy law) and regulations (renewable energy pricing) that could improve the investment climate and renewable project attractiveness, respectively. Additionally, the mechanism in replacing CFPP asset immediately with renewables have to be proposed. With a reasonably sound mechanism, PLN and IPPs would have welcomed the CFPP retirement plan.

Government shall establish a national commission or task force across government agencies to plan a just energy transition and CFPP retirement by the end of this year, including renegotiation with the IPP (G20 News 2022). The multi-faceted aspect of CFPP retirement must be addressed for the policy to be supported by the stakeholders. Learning from Germany's example, the establishment of a national commission/task force has proven to be one of the options to tackle this challenge. This is more important in Indonesia's case, as multiple government agencies have discussed and harmonized around the CFPP retirement (e.g. Coordinating Ministry of Maritime and Investment, Ministry of Finance, Ministry of Energy and Mineral Resources), but some are yet included in the discussion (e.g. Ministry of National Development Planning, Ministry of Environment and Forestry). There is also no clarity on the leading government institution for resolving CFPP retirement issue right now.

The national energy transition platform/mechanism, currently being discussed, should also consider the findings of this report, particularly the financing needs for implementing the just principle. The socio-economic aspects of the CFPP retirement should also consider the impact on the sub-national government and on the workers who are yet to have visible ways to communicate their aspirations. Academics could also be involved to gain independent views on the possible solution and agreement.

Lastly, the negotiation of CFPP contract between PLN and IPP should be initiated to weigh in the potential additional cost while not jeopardizing the investment climate in Indonesia. The list of the CFPP owned by IPP should also be assessed to determine whether there is also interest from the owner, sponsor or other shareholders in retiring their coal asset. The task force could also help mediate this process.

Early phaseout will require international support, in the form of grant and concessional loan and carbon finance. There is a need to assess suitable financial mechanisms for retiring coal plants owned by IPP. Eventhough the social-economy benefits of CFPP early retirement outweigh its cost, there is still a need to provide international funds support. The existence of such fund would help the government of Indonesia to make a firm decision in pushing for CFPP retirement and convince other stakeholders involved. There should also be a different approach for IPP coal asset, and can be considered case by case basis. Reasons are that IPP has a take-or-pay contract with PLN, and phasing-out their coal assets means convincing IPP in giving up certain revenue based on their contract.

However, there are some IPPs whose owner, sponsor, or other shareholders who might already have interest in phasing-out CFPP early, and therefore could be considered priority in terms of contract negotiations. Another way that could be considered, especially for very young coal fleet, is partly reducing their take-or-pay limit contract and introduce substitute contract that allow for coal power flexible operation (IESR, 2022a). The coal fleet will still need to consider phase-out when reaching around 20 years of lifetime or when economic return for the IPP is sufficient.

Government of Indonesia needs to identify potential society impacts of coal phase out on local communities. Social protection and financial assistance packages shall be developed and implemented along with the retirement schedule. The number of workers (CFPP and coal industry) affected are substantial, reaching hundred thousands of jobs over the 25 years span. There are also impacted industries in the supply chain (e.g. coal shipping, logistics for CFPP) that are yet quantified in this report. The social-economic impact is larger considering these workers contribution to their own family and community. Bridging their needs and even transfer of jobs (to green jobs for example) should be one major focus of the just transition process. Again, accommodating this process needs an implementing regulatory framework that is also supported in the development policies (RPJMN/mid-term development plan).

Our analysis uses the best data available to provide the first systematic assessment of the financing need to implement an accelerated and just transition of Indonesia’s coal-fired power plants. The proposed framework includes several other costs and benefits metrics that are not quantified due to data limitations, such as the avoided air pollution control retrofitting cost, tax income losses, consumer energy access, green job opportunities, and so forth (see Technical Appendix for more description and discussion). While our benefits and costs estimates tend to be conservative, it represents the main chunk on the cost side. Future research will continue to improve data and method to quantify more outcome metrics, assess financing need at the subnational level, and explore different financing mechanisms to cancel and retire projects.

Bibliography

African Development Bank. 2022. 'Joint Statement of the Government of the Republic of South Africa and the African Development Bank in Relation to South Africa's Just Energy Transition Process'. African Development Bank - Building today, a better Africa tomorrow. https://www.afdb.org/en/news-and-events/press-releases/joint-statement-government-republic-south-africa-and-african-development-bank-relation-south-africas-just-energy-transition-process-51926 (August 1, 2022).

antaranews.com. 2022. 'DPD: Revisi UU Energi Perlu Utamakan Konservasi Lingkungan Hidup'. Antara News. https://www.antaranews.com/berita/2732421/dpd-revisi-uu-energi-perlu-utamakan-konservasi-lingkungan-hidup (August 2, 2022).

Asian Development Bank. 2021. 'ADB, Indonesia, the Philippines Launch Partnership to Set Up Energy Transition Mechanism'. Asian Development Bank. https://www.adb.org/news/adb-indonesia-philippines-launch-partnership-set-energy-transition-mechanism (August 1, 2022).

Bisnis. 2021. 'Gawat, Oversupply Pembangkit Listrik Jawa-Bali Bisa Capai 61 Persen - Ekonomi Bisnis.Com'. Bisnis.com. https://ekonomi.bisnis.com/read/20211125/44/1470530/gawat-oversupply-pembangkit-listrik-jawa-bali-bisa-capai-61-persen (December 21, 2021).

BNEF, and IESR. 2021. Scaling Up Solar in Indonesia: Reform and Opportunity. BloombergNEF.

detikcom. 2022. '3 Fakta Rencana RI Pensiunkan 5,5 GW PLTU'. detikfinance. https://finance.detik.com/energi/d-5935301/3-faktarencana-ri-pensiunkan-55-gw-pltu (August 1, 2022).

G20 News. 2022. 'Indonesia Launched Energy Transition Mechanism Country Platform – G20 Presidency of Indonesia'. https://g20.org/indonesia-launched-energy-transition-mechanism-country-platform/ (August 1, 2022).

IESR. 2022a. Flexible Thermal Power Plant: An Analysis of Operating Coal-Fired Power Plants Flexibly to Enable the High-Level Variable Renewables in Indonesia's Power System. Institute for Essential Services Reform. https://iesr.or.id/pustaka/pembangkit-listrik-tenaga-panas-fleksibel-analisis-pengoperasian-pembangkit-listrik-tenaga-batubara-secara-fleksibel-untuk-memungkinkan-integrasi-tingkat-tinggi-energi-terbarukan-di-sistem-tenaga-lis.

———. 2022b. Indonesia Energy Transition Outlook 2022. https://iesr.or.id/en/pustaka/indonesia-energy-transition-outlook-ieto-2022.

Katadata. 2021. 'PLTU 9,2 GW Pensiun Dini sebelum 2030, Cuma 40% yang Diganti EBT - Energi Baru'. Katadata.co.id. https://katadata.co.id/happyfajrian/ekonomi-hijau/618697bae4fe2/pltu-9-2-gw-pensiun-dini-sebelum-2030-cuma-40-yang-diganti-ebt (March 24, 2022).

Kompas. 2020. 'Tolak PLTU Indramayu, Warga Bentuk Jatayu dan Berjuang hingga ke Jepang (2) Halaman all - Kompas.com'. Kompas.com. https://regional.kompas.com/read/2020/06/08/08380091/tolak-pltu-indramayu-warga-bentuk-jatayu-dan-berjuang-hingga-ke-jepang-2?page=all (August 1, 2022).

Mongabay. 2019. 'Nasib Warga Sekitar PLTU Celukan Bawang, Bakal Makin Sulit dengan Perluasan Pembangkit'. Mongabay.co.id. https://www.mongabay.co.id/2019/09/15/nasib-warga-sekitar-pltu-celukan-bawang-bakal-makin-sulit-dengan-perluasan-pembangkit/ (August 1, 2022).

Republic of Indonesia. 2021. Update National Determined Contribution. https://www4.unfccc.int/sites/ndcstaging/PublishedDocuments/Indonesia%20First/Updated%20NDC%20Indonesia%202021%20-%20corrected%20version.pdf.

UNCC. 2021. 'Global Coal to Clean Power Transition Statement'. UN Climate Change Conference (COP26) at the SEC – Glasgow 2021. https://ukcop26.org/global-coal-to-clean-power-transition-statement/ (May 19, 2022).

VOI. 2022. 'Pandemi Melandai, Ini Peran PLTU Celukan Bawang Bantu Bali Bangkit'. VOI - Waktunya Merevolusi Pemberitaan. https://voi.id/ekonomi/147365/pandemi-melandai-ini-peran-pltu-celukan-bawang-bantu-bali-bangkit (August 1, 2022).

Warta Ekonomi. 2022. 'Kejar Target NZE 2060, DEN Berencana Revisi RUEN 2017'. Warta Ekonomi.co.id. https://wartaekonomi.co.id/read405893/kejar-target-nze-2060-den-berencana-revisi-ruen-2017 (August 2, 2022).

Technical Appendix

S1. GCAM and Net Zero Pathway

The Global Change Assessment Model (GCAM 5.4, jgcri.github.io/gcam-doc/) is an integrated assessment model that represents and links the world economy, energy, agriculture, land-use, water, and climate systems. It is designed to explore interactions between complex systems and gain insights about long-term trends. GCAM represents 32 geopolitical regions, and represents land use and agriculture in 384 land regions nested within 235 water basins. GCAM has been widely used to produce scenarios for international and national assessments, including the Intergovernmental Panel on Climate Change (IPCC) report[1,2,3,4], the Representative Concentration Pathways (RCPs)[5], and the Shared Socioeconomic Pathways (SSPs)[6].

Specifically, GCAM takes in assumptions about population growth and changes in labor productivity, along with representations of resources, technologies, and policies, and solves for the equilibrium prices and quantities of various energy, agricultural, and GHG markets in each five-year period from 2010 (the calibration year) to 2100 at different spatial resolutions.

To model Indonesia's net zero pathway, Indonesia's energy CO_2 emissions were linearly constrained to reach net zero by 2050. Other global regions with net zero targets -- including Canada, China, Japan, South Korea, the European Union, and the United States -- were also constrained in a similar fashion, to account for their potential influence on Indonesia through global energy markets. Canada, Japan, South Korea, U.S., and E.U. linearly reach net zero GHG emissions by 2050, and China linearly reaches net zero CO_2 emissions by 2050. In addition, a separate rest-of-the-world emissions constraint linearly reaches net zero CO_2 emissions by 2050, which is in line with a 1.5°C scenario.

We calibrated electricity generation to more closely match Indonesia's current trends. Generation values for oil, gas and coal in 2020 were recalibrated to match Institute for Essential Services Reform (IESR)'s 2050 decarbonization report[7]. Additionally, nuclear wasn't chosen by the model in the study due to the cost and installation duration. Cost assumptions for power sector technologies were adjusted according to a report prepared by the Directorate General of Electricity (Table S8) so that they more closely aligned with the costs of technologies in Indonesia.

1 J. Rogelj, D. Shindell, K. Jiang, "Mitigation pathways compatible with 1.5 °C in the context of sustainable development" (2018).
2 IPCC, "Climate change 2001: Mitigation: Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change" (Cambridge University Press, Cambridge, 2001).
3 IPCC, "Climate change 2007: Mitigation of climate change – contribution of working group III to the fourth assessment report" (Cambridge University Press, Cambridge, 2007).
4 IPCC, Climate Change 2014 Mitigation of Climate Change: Working Group III Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge University Press, Cambridge, 2014).
5 A. M. Thomson et al., Climatic Change. 109, 77–94 (2011).
6 K. Calvin et al., Global Environmental Change. 42, 284–296 (2017).
7 https://iesr.or.id/en/pustaka/deep-decarbonization-of-indonesias-energy-system-a-pathway-to-zero-emissions-by-2050

S2. Retirement Priority Ranking

S2.1. Data

For the retirement priority ranking, we used existing coal power plant dataset from the Global Coal Plant Tracker (Jan 2022)[8], and assessed plant-level profitability and quantified environmental impact indicators based on multiple datasets (Table S1).

Table S1. Data Description

Variable	Dataset	Resolution	Year	URL
Technical attributes and locations of coal power plants	Global Coal Plant Tracker published by Global Energy Monitor (Jan 2022)[9]	Plant level	2021	https://endcoal.org/global-coal-plant-tracker/
Electricity price and coal price	PLN Statistics (PT PLN), 2018; Regional Energy Modelling in four Indonesian Provinces, 2019	Provincial level	2018	STATISTICS PLN 2018; ea-energianalyse.dk
Annual $PM_{2.5}$ concentration	Global (GL) Annual $PM_{2.5}$ Grids from MODIS, MISR and SeaWiFS, v4.03	0.01° x 0.01°	2016	https://sedac.ciesin.columbia.edu/data/set/sdei-global-annual-gwr-pm2-5-modis-misr-seawifs-aod-v4-gl-03
Overall water risk	Aqueduct Water Risk Global Maps 2.1 Data[10]	Polygons	2010	https://www.wri.org/resources/data-sets/aqueduct-global-maps-21-data

Our analysis focuses on the existing and construction/PPA projects owned by the state-owned public utility PLN and Independent Power Producers (IPP) (72 plants, 43.4 GW). Among these,IPP owns 27.7 GW and PLN owns 15.7 GW. IPP owns majority of the capacity built within the past decade, while the oldest plants (30~40 years) belong to PLN (Figure S1 top panel). IPP owns majority of the units larger than 600 MW (Figure S1 middle panel). IPP owns majority of the units with super- and ultra super-critical technologies (Figure S1 bottom panel). Out of the 12.3 GW of new capacity to be added, 9.2 GW is developed by IPP, including all three new projects with PPA contract.

[8] Global Coal Plant Tracker, Global Energy Monitor, Jan (2022).
[9] Global Coal Plant Tracker, Global Energy Monitor, Jan (2022).
[10] Gassert, F., M. Luck, M. Landis, P. Reig, and T. Shiao. (2014). Aqueduct Global Maps 2.1: Constructing Decision-Relevant Global Water Risk Indicators. Working Paper. Washington, DC: World Resources Institute. Available online at http://www.wri.org/publication/aqueduct-globalmaps-21-indicators

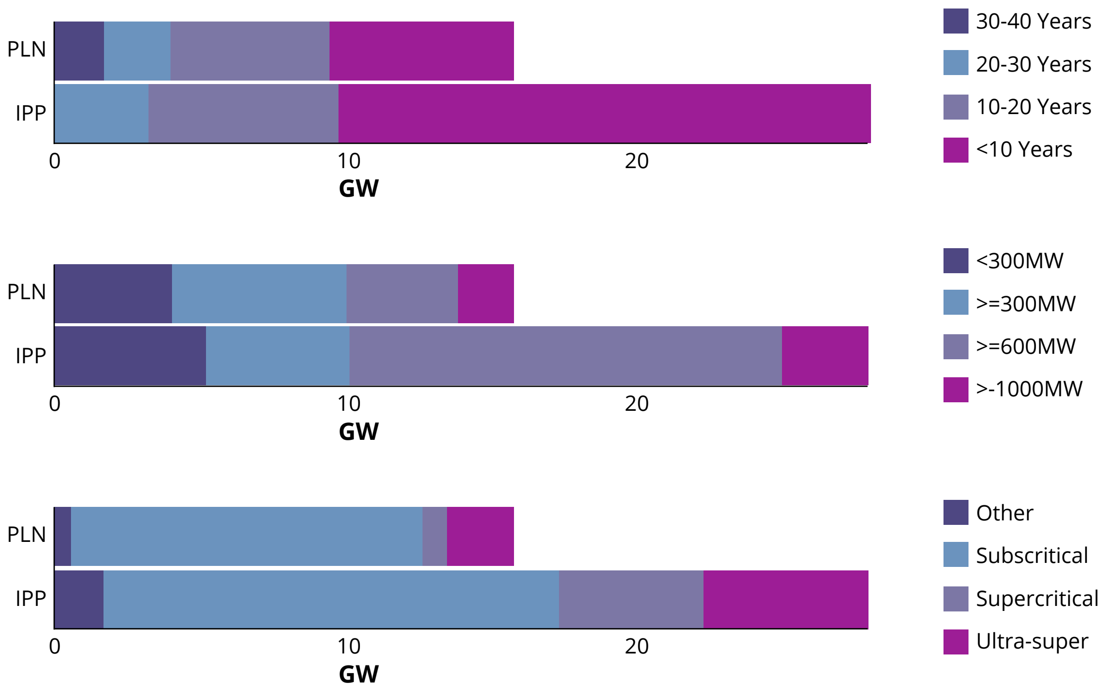


Figure S1. Distribution of CFPPs by plant age, size and technology

S2.2. Metrics Identification

We conducted a systematic evaluation to strategize the Indonesia coal phaseout. We developed the plant-by-plant retirement algorithm based on the technical attributes, profitability, and environmental impacts of the coal power plants (Figure S2). Each of the three dimensions is quantified through a set of criteria. The score of technical attributes is based on the plant age, size, and combustion technology. Profitability is based on capacity weighted annual gross profits. The score of environmental impacts is based on the CO_2 emission rates, air pollution and health impacts, and water impacts.

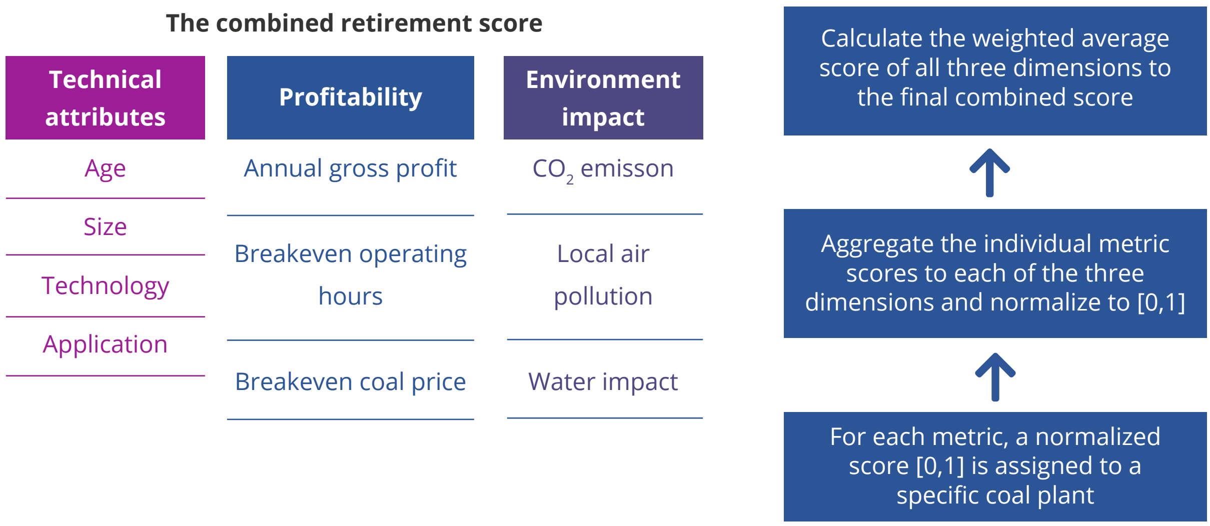


Figure S2. Methodology of the plant-by-plant retirement algorithm from Cui et al., 2021[11]

[11] Cui, R.Y., Hultman, N., Cui, D. et al. A plant-by-plant strategy for high-ambition coal power phaseout in China. Nat Commun 12, 1468 (2021). https://doi.org/10.1038/s41467-021-21786-0

Technical Attributes

Technical attributes of individual plants are described using three metrics: age (vintage year), size (capacity), and combustion technology. Plant age is quantified using the vintage year and is assigned with a normalized score from 0 to 1 based on the first year of operation. Plant size is categorized into four groups: <300MW, 300-600MW, 600-1000MW , and >=1000MW. The categories are based on the commonly adopted combustor sizes. The size groups are given rank scores [1,4] according to the unit sizes ranging from <300MW to >=1000MW. The rank scores [1,4] are normalized into [0,1] to eliminate the issue of data scaling.

Combustion technologies are grouped into ultra-supercritical, supercritical, subcritical, and others, ranked from the most to the least efficient with a decreasing score from 4 to 1. Similarly, the rank scores [1,4] are normalized into [0,1].

Profitability

Gross profit is estimated by the difference between the annual revenue and annual cost of the coal-fired power plants.

$$\textit{Net profit} = \textit{Revenue} - \textit{Cost} \quad (2.1)$$

The annual revenue is estimated by electricity price and amount of electricity generated by the coal-fired power plants.

$$\textit{Revenue} = P_{elecoal} * Q_{elecoal} \quad (2.2)$$

Where, $P_{eleccoal}$ is the electricity (sourced from coal) price by province. $Q_{eleccoal}$ is the electricity generated by coal power plants.

$Q_{eleccoal}$ is estimated by the product of coal plant capacity (MW) and operating hours (hr). Plant-level capacity is derived from Global Coal Plant Tracker (Jan 2022), and the national level operating hours of coal power plants are estimated using the 2021 Indonesian total coal power electricity generation divided by existing coal capacity.

The annual costs of coal-fired power plants are the sum of delivered fuel cost (*coalcost*), variable Operating and Maintenance (O&M) cost (*varOM*), fixed O&M costs (*fixOM*), and additional costs, including environmental costs and tax (*add*), as follows:

$$\textit{Cost} = \textit{coalcost} + \textit{varOM} + \textit{fixOM} + \textit{add} \quad (2.3)$$

Coal is the main fuel to support the operation for coal-fired power plants. It is calculated in Equation 2.4.

$$\textit{coalcost} = \textit{coalcost}_u / \alpha * H \quad (2.4)$$

Where coalcost is measured in the price of delivered coal, including costs of purchasing and transportation. Unitary delivered coal price ($coalcost_u$) by province is from Regional Energy Modelling results in four Indonesian provinces and other provinces from PLN Statistics 2018. α is standard coal consumption rate, referring to lower heating value (LHV), 27,778.62 Btu/t. H represents the heat rate, which is dependent on the technology, age, and size of the coal power plants, in Btu/kWh.

$$H = H_{base} * \theta \quad (2.5)$$

Where H_{base} denotes the base heat rate, dependent on the technology (Global Coal Plant Tracker). θ is the adjustment multiplier, based on the size and age of the coal power plants, ranging from 1-1.45.

The capacity-adjusted multipliers increase when capacity decreases. We assume the multiplier for plants with capacity ≥ 1000MW as 1, 600MW ≤ capacity < 1000MW as 1.05, 300MW ≤ capacity < 600MW as 1.1, and capacity <300MW as 1.2. Age effects on the heat rate is linear on top of the capacity-adjusted heat rate, which is calculated by Hcap + (age/100 - 0.1)[12].

The Operation and Maintenance (O&M) costs include the variable O&M cost (varOM) and fixed O&M (fixOM) cost:

$$\textit{varOM} = \textit{varOM}_u * Q_{elecoal} \quad (2.6)$$
$$\textit{fixOM} = \textit{fixOM}_u * \textit{Capacity} \quad (2.7)$$

Variable O&M cost refers to long run marginal cost that measures the cost to produce a unit of electric energy, 2.76 $(2015)/MWh in this study; while fixed O&M cost captures the recurring annual cost that occurs regardless of the size or architecture of the power system, 11.03 $(2015)/kW/yr.

[12] International Energy Agency (IEA). (2012). Technology Roadmaps: High-efficiency, low-emissions coal-fired power generation. p.17.

Environmental Impacts

Our assessment of environmental impacts integrates three elements — 1) global climate change, 2) local air pollution and human health, and 3) water impact.

First, to assess the impact of individual coal power units on global climate change, the CO_2 emission rate is estimated at the unit-level. Here, the CO_2 emission rate refers to the amount of CO_2 emitted per unit of electricity generation. Annual CO_2 emissions are calculated as follows:

$$\textit{Annual } CO_2 = elecgen * \gamma * H * E * c \qquad (2.8)$$

$$elegen = Capacity * T \qquad (2.9)$$

Where, Annual CO_2 is the annual CO_2 emissions, in Mt; elecgen is the electricity generation, calculated by plant-level capacity (Capacity) and operating hours (T), in kWh/yr; γ is the conversion coefficient, 1.06×10-9 TJ/Btu; H represents the heat rate in Btu/kWh; E is the carbon content of coal, in tC/TJ. Carbon content is dependent on coal type. c is constant, which is equal to 12/44×10-9.

The CO_2 emission rate depends on plant efficiency as well as the type of coal combusted. In general, emissions rates increase as a plant gets older, smaller and/or uses a less efficient combustion technology. Coal power units with relatively higher CO_2 emission rates estimated are units which need to be retired first, with lower rank scores assigned.

The air pollution and human health risk is assessed by looking at the population weighted $PM_{2.5}$ concentration level at a plant's location. We used Global (GL) Annual $PM_{2.5}$ Grids from MODIS, MISR and SeaWiFS Aerosol Optical Depth (AOD) (v4.03 of 2016)[13] and UN WPP-Adjusted Population Density from NASA Socioeconomic Data and Applications Center (SEDAC) (v4.11 of 2015)[14]. Air pollution and its potential threats on human health is quantified using $PM_{2.5}$ exposure level, which is calculated using population-density-weighted PM2.5 annual concentration. Unit-level $PM_{2.5}$ exposure is retrieved from the $PM_{2.5}$ exposure map with national coverage using coordinates of individual units. Units located in highly-polluted and highly-populated areas, which can be indicated by higher $PM_{2.5}$ exposure level, are given lower rank scores.

Water impact is estimated with the water risk level of a plant's location using a similar method. The water risk score applied in our research is from Aqueduct Global Maps (v2.1 of 2010)[15], derived from a framework of 12 global water-related risk indicators. This Water Risk Index (WRI) provides a good representation of the physical, regulatory and reputational water risk level. The well-defined comprehensive WRI of a given unit's location is used to indicate the potential reduction in local water impacts by closing that coal unit. It represents the potential reduction in water impact by closing coal units in that gridded cell. Therefore, units in regions facing more severe water scarcity receive lower rank scores.

[13] Hammer, M. S., A. van Donkelaar, C. Li, A. Lyapustin, A. M. Sayer, N. C. Hsu, R. C. Levy, M. J. Garay, O. V. Kalashnikova, R. A. Kahn, M. Brauer, J. S. Apte, D. K. Henze, L. Zhang, Q. Zhang, B. Ford, J. R. Pierce, and R. V. Martin. 2022. Global Annual PM2.5 Grids from MODIS, MISR and SeaWiFS Aerosol Optical Depth (AOD), 1998-2019, V4.GL.03. Palisades NY: NASA Socioeconomic Data and Applications Center. https://doi.org/10.7927/fx80-4n39.
[14] Center for International Earth Science Information Network (CIESIN), Columbia University. 2018. Documentation for the Gridded Population of the World, Version 4 (GPWv4), Revision 11 Data Sets. Palisades NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H45Q4T5F
[15] Gassert, F., M. Luck, M. Landis, P. Reig, and T. Shiao. (2014). Aqueduct Global Maps 2.1: Constructing Decision-Relevant Global Water Risk Indicators. Working Paper. Washington, DC: World Resources Institute. Available online at http://www.wri.org/publication/aqueduct-globalmaps-21-indicators1 Data Sets. Palisades NY: NASA Socioeconomic Data and Applications Center (SEDAC). https://doi.org/10.7927/H45Q4T5F

S2.3. Retirement Score Calculation

We take three steps to develop the retirement priority: 1) Assign a normalized rank score [0,1] for each metric; 2) Average the individual metric scores under each dimension and get a normalized dimensional score [0,1]; and 3) Take the mean of the dimensional scores as a combined score [0,1].

A lower score of the combined metric indicates that the plant could be retired early due to poorer technical attributes, poor economic performance, and higher environmental impact, while a higher score closer to one indicates the plant could be the last to retire (Fig S2). Overall, plants to retire first are older, smaller, less efficient plants located in highly air polluted and water scarce regions.

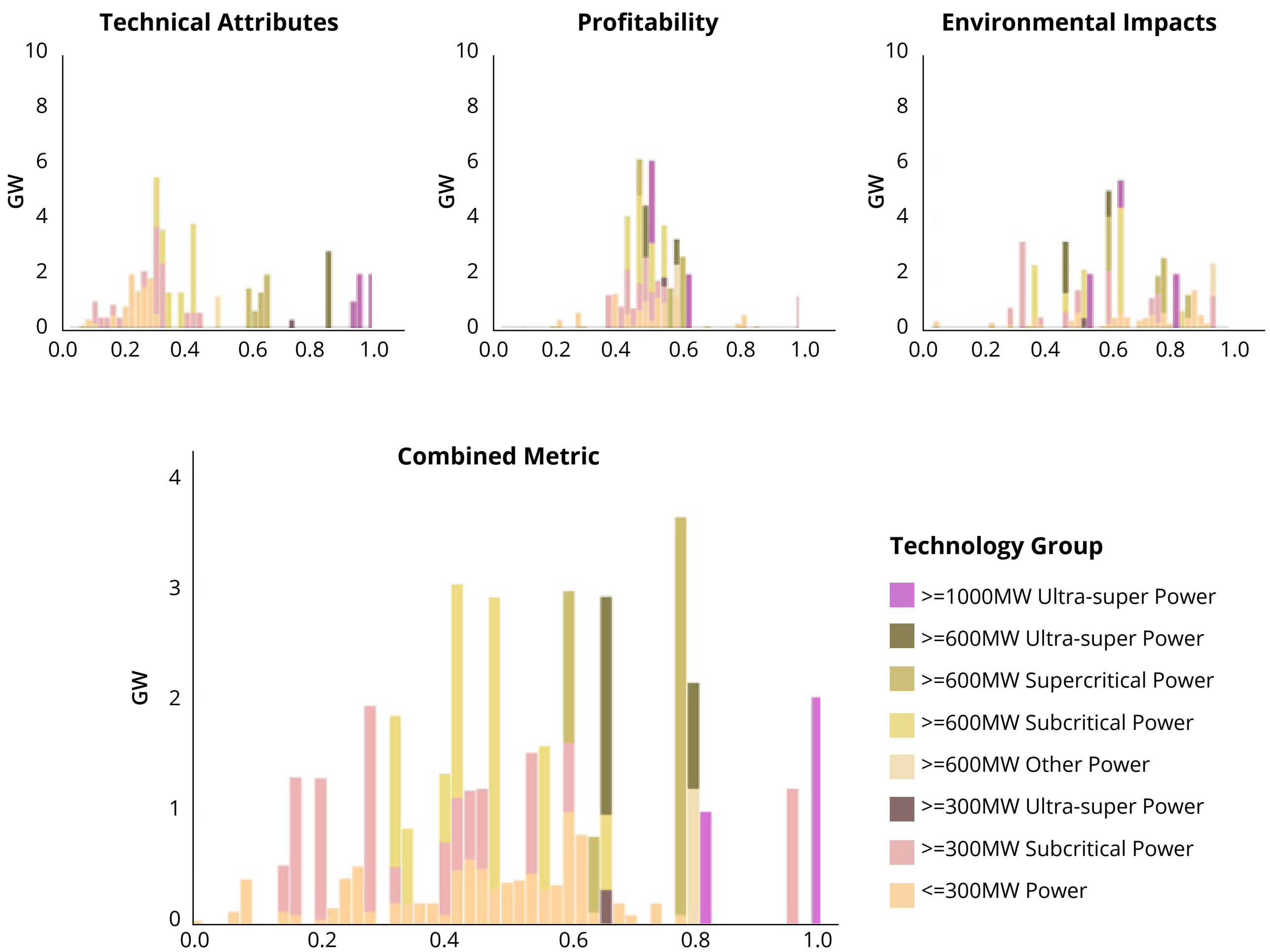


Figure S3. Scores of technical attributes, profitability, environmental impacts, and the combined score of the three dimensions for individual coal plants.

S2.4. Low Hanging Fruit Plants

To identify units which are likely to retire first based on technical attributes, profitability, and environmental impacts, we define low-hanging fruit units (LHF) as the units that receive a below-median score in all three dimensions evaluated (Figure S3). These units are likely to retire first regardless of which criteria are prioritized for retirement.

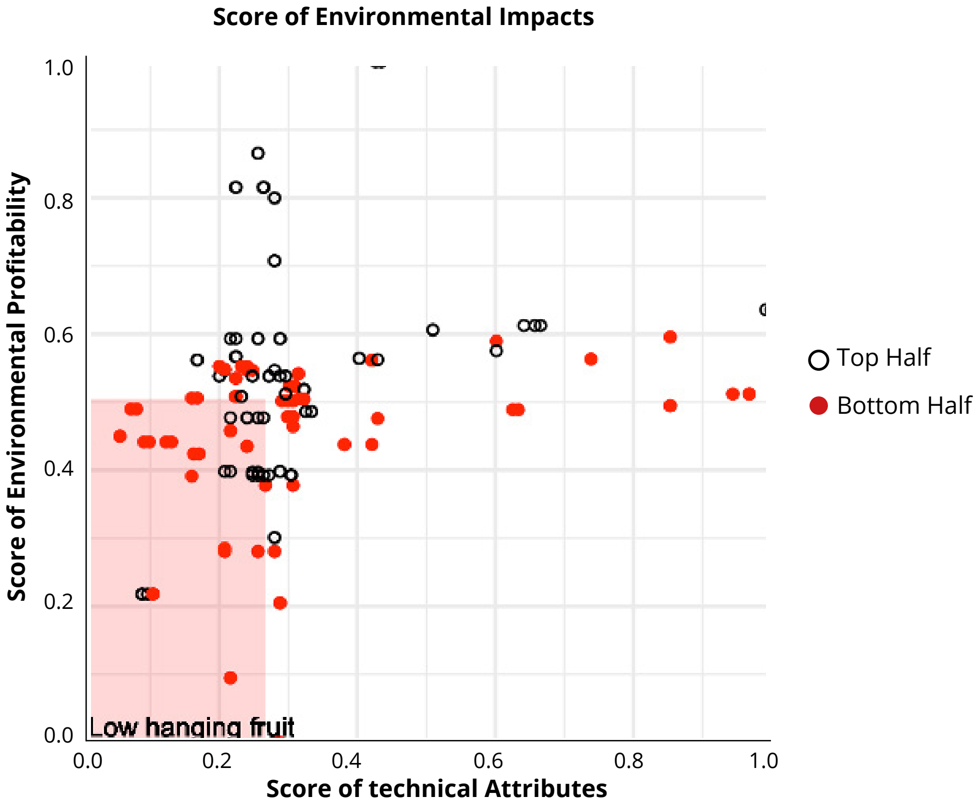


Figure S4. Scores of technical attributes, profitability, and environmental impacts for the low-hanging fruit plants.

S3. Benefits and Costs Quantification

In order to quantify the benefits and costs of phasing out coal in Indonesia, we developed a comprehensive framework examining metrics associated with economic, social, and environmental outcomes. The framework also groups the metrics by the associated stakeholder: coal-related industry, the Indonesian government, and the public.

Tabel S2. Framework of economic, social and environmental metrics to quantify benefits and costs associated with different stakeholders.

Economic	Social	Environment
Stranded assets for PLN	Fiscal support for job losses (CFPP and supply chain)	Avoided air pollution control retrofit cost
Decommissioning cost	Job losses compensation (CFPP and supply chain)	Reclamation cost
Avoided coal electricity subsidies	Public health benefit	Air quality improvement
Early retirement compensation for IPP	Human development	Water savings and water quality
State coal revenue losses	Green job growth	GHG emission reduction
Tax income losses	CFPP support to surrounding community	
Policy incentives for RE deployment	Job and income losses CFPP and supply chain)	
Energy access		

Coal-related Industry Government Public **Benefit** **Cost** **Uncertain Outcomes**

S3.1. Economic Outcomes

Stranded Assets and Early Retirement Compensation

We quantified the potential costs related to stranded assets from PLN and IPP coal plant retirements by calculating the remaining value of premature retired plants, assuming linear cost depreciation and a 30-year designed economic lifetime (Equation 3.1).

$$stranded\ assets\ value\ = OCC \times K \times \frac{(L-R)}{L} \quad \textbf{(3.1)}$$

Where OCC indicates overnight capital cost of the power plant, K indicates capacity, L indicates expected lifetime, and R indicates retirement age of each plant.

The analysis used the central cost estimates of coal power plants by technology group, and the lower and upper estimates are used in the sensitivity analysis (Table S3)[16].

CFPP stranded assets account for the largest share of the costs quantified through 2050. With a minimum of a 20-year lifetime, less than 40% of today's CFPP assets value will be stranded (Figure S5).

[16] Catalogue for Generation and Storage of Electricity. (2021). Technology Data for the Indonesian Power Sector. p.104-106.

Tabel S3. Cost estimates of coal power plant by technology

Technology	Cost in 2020 ($/KWe)			Cost in 2050 ($/KWe)		
	Central	Lower	Upper	Central	Lower	Upper
Subcritical	1650	1000	1700	1550	1050	1700
Supercritical	1400	1050	1750	1320	990	1650
Ultra-suoercritical	1520	1140	1910	1430	1070	1790

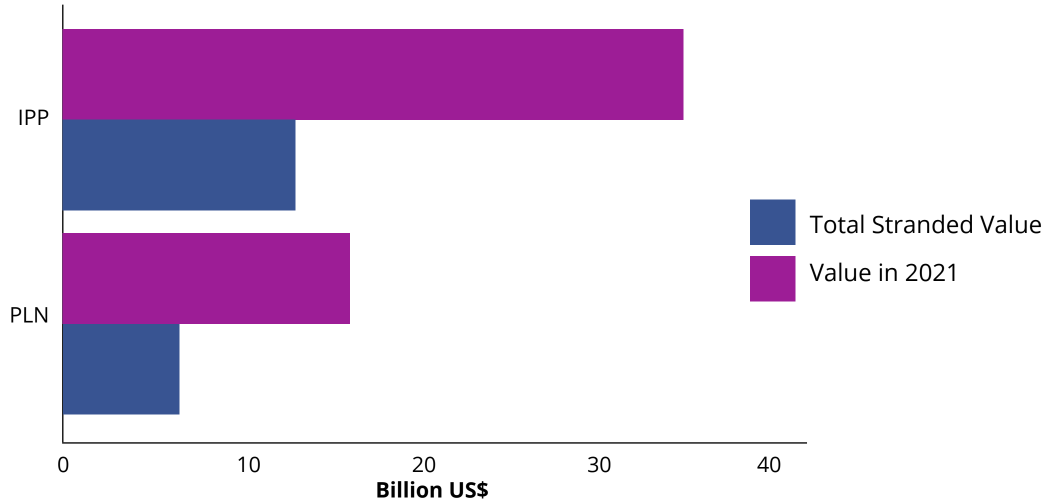


Figure S5. Total stranded value and value in 2021 for IPP and PLN plants

Decommissioning Cost

To date, none of Indonesia's CFPP fleet has been decommissioned. Hence, to quantify the decommissioning cost, we look at a decommissioning example in India, the NTPC 1000 MW Badarpur Power Plant[17]. The breakdown of the cost per unit capacity, in MW, is detailed in Table S4.

In our calculation, we only consider the total cost per MW of all components shown in the table. Hence, the decommissioning cost for each year leading up to 2045 is simply obtained from the total retired capacity each year multiplied by the total cost per MW.

[17] Source: Energy Sector Management Assistance Program. 2021. Coal Plant Repurposing for Ageing Coal Fleets in Developing Countries. ESMAP Technical Report 016/21. Washington, DC: World Bank. License: Creative Commons Attribution CC BY 3.0 IGO

Table S4. Decommissioning cost breakdown

Item	Cost (US$ Million/1000 MW)
Employee cost	7.11
Station overheads	24.14
O&M expenses	3.9
Pre-demolition costs: environmental regulation (asbestos removal)	0.09
Demolition costs	4.05
Cost combustion residuals (ash pond)	15.72
Coal storage area cleanup	3.1
Total	**58.11**

Avoided Coal Electricity Subsidies

We look into the historical electricity subsidy provided by the government for PLN in the last five years (2015-2020). The historical electricity subsidy for years 2015-2017 is taken from OECD data[18], while the 2018-2020 data is taken from the Ministry of Finance annual report[19]. The subsidy share for CFPPs is equal to the generation share, which we take from PLN's Electricity Supply Business Plan (RUPTL)[20].

Average annual subsidy per kWh of electricity is calculated by dividing the subsidy by total coal electricity generation each year, and averaging over five years. The avoided subsidy is calculated by comparing the coal electricity subsidies from each coal power plant unit in our coal plant retirement scenario (20-year guaranteed lifetime with limited generation to comply with 1.5°C pathway) versus the business-as-usual scenario (with the BAU scenario defined as all CFPP reaching a 30-year lifetime with constant utilization rate as of today) (Equation 3.2).

Avoided coal electricity subsidies =

$$\sum_{1}^{N}\left(AS \times \left(\left[K \times CF_{constant}\right] - \left[K \times CF_{varied}\right]\right)\right) \quad \textbf{(3.2)}$$

Where AS is the average subsidy per kWh, K is coal plant capacity, $CF_{constant}$ is capacity factor that is assumed constant based on historical data, and CF_{varied} is capacity factor with assigned value generated for each coal power plant from our 1.5°C scenario using GCAM.

CF_{varied} for each year is calculated using γ, the utilization reduction ratio, estimated based on the ratio of capacity in our 1.5°C-compatible retirement pathway under 20-year guaranteed lifetime scenario with reduced utilization, and the capacity pathway under constant utilization scenario (Equation 3.3).

$$CF_{varied} = CF_{constant} \times \gamma \quad \textbf{(3.3)}$$

[18] oecd.stat. For electricity subsidy 2015-2017. https://www.oecd.org/fossil-fuels/data/
[19] Ministry of Finance. APBN Kita. for electricity subsidy 2018-2020
[20] PLN. 2021. Rencana Usaha Penyediaan Tenaga Listrik (RUPTL) PT PLN (Persero) 2021-2030.

State Coal Revenue Losses

We first estimate how much electricity is generated from one ton of coal in Indonesia using historical data over a 10-year period (2011-2020). As the commodity price of coal is constantly changing, we use the average price of Indonesian coal reference price (HBA)[21] for each year as the base coal price, which we later use as reference price to compare with the revenue that the government receives from each ton of coal sales. For this part we only use 2019-2020 data as reference due to lack of data availability.

Using both estimates from the two exercises above (the Indonesian coal average price and total state revenue per ton of coal), we could estimate the amount of state revenue losses for each coal sales (in %). We then calculate state revenue using the constant of state revenue losses multiplied by the coal consumption and coal reference price for each year and for each plant. As a reference, we use coal commodity price forecast from the World Bank (published in October 2021)[22].

State coal revenue losses =

$$\sum_{1}^{N}\left(CP \times SR \times \left(\frac{[K\times CF_{constant}]-[K\times CF_{varied}]}{EC} \right) \right) \quad \textbf{(3.4)}$$

Where N indicates each year until retirement, CP is the WB coal Australia price forecast in USD/ton (if the value is not directly determined in the reference, then it will use latest forecast value in the previous year), SR is the state revenue constant conversion (percentage of state revenue gain for each ton of coal sales ~5.565%) in %, and EC is the electricity generated for each ton of coal burned in coal power plants in kWh/ton.

$$EC = \frac{\alpha}{H} \quad \textbf{(3.5)}$$

Where α is standard coal consumption rate, referring to lower heating value (LHV), 27,778.62 Btu/ton. H represents the heat rate, which is dependent on the technology, age, and size of the coal power plants, in Btu/kWh.

$$H = H_{base} * \theta \quad \textbf{(3.6)}$$

Where H_{base} denotes the base heat rate, dependent on the technology (Global Coal Plant Tracker) . θ is the adjustment multiplier, based on the size and age of the coal power plants. Age effects on the heat rate is linear on top of the capacity-adjusted heat rate, which is calculated by H_{cap} + (age/100 - 0.1).

Metrics Not Quantified

Due to limits in data availability, we were unable to quantify all of the metrics that were identified in the economic dimension. The following metrics were not quantified:

- **Energy access:** Change in electricity costs.
- **Tax income losses:** Loss of corporate tax revenue from coal power companies to the national government.
- **Incentives for renewable energy deployment:** Monetary incentives that would scale up renewable energy to meet electricity demand with a stable grid.

Although we did not quantify incentives for renewable energy deployment, we have quantified the renewable energy investment needed to make the transition (See Section 4).

[21] Ministry of Energy and Mineral Resources. Harga Acuan. https://www.minerba.esdm.go.id/harga_acuan
[22] World Bank (2021). Commodities Price Forecast. https://thedocs.worldbank.org/en/doc/ff5bad98f52ffa2457136bbef5703ddb-0350012021/related/CMO-October-2021-forecasts.pdf

S3.2. Social Outcomes

Job and Income Losses (CFPP and Supply Chain)

To calculate the income losses for both CFPPs and the supply chain as a whole, we relied on Indonesia's state revenue data. CFPP income losses were calculated through an estimation of the number of jobs lost per year multiplied by the average annual income for workers. The job losses per year were calculated at a plant-by-plant level, assuming that plants of higher capacity lose more workers per MW of reduced utilization. The job and income losses were also separated into losses experienced by PLN and IPP.

Table S5. Number of workers and yearly income loss per MW by capacity class

Capacity Class	Workers/MW[23]	Total Yearly Income Loss/MW
>600 MW	0.15	$484.89
300-600 MW	0.44	$1,380.05
100-300 MW	0.60	$1,882.96
<100 MW	1.51	$4,737.77

To determine the power plant income losses at PLN and IPP plants, we applied the annual ratio of PLN to IPP plants obtained from state revenue losses. The ratio was used to separate the losses experienced by PLN and IPP.

Reductions in upstream coal power generation and employees' income will cause downstream pressure on mining and the broader coal industry, so we assume that there will be a proportionate reduction in total coal mining production. To calculate coal mining income losses, we multiplied the annual estimate for reductions in coal consumption by the estimated income loss per million tons of coal production. In this scenario, we assume that for every million tons of coal that are not produced, there will be $1,465,910.35 of lost income. This assumption is based on the typical net income for each employee class[24] and estimated workers per million tonnes of coal[25]. To separate the mining income losses into those incurred by PLN mining and IPP operations, we applied the same ratio used above.

Fiscal Support for Job Losses (CFPP)

We calculated the public fiscal support for job losses by finding current and historical low, medium, and high support packages in other countries (Tables S6). A review of existing public support packages found that aid tends to fall into three categories: health, income compensation, and rehiring. Given the relevance to Indonesian coal phaseout, our analysis focused on rehiring supports, which include hiring incentives (e.g. giving companies funds with which to hire former coal workers), relocation support, and retraining funds. In each country identified with existing or pre-existing rehiring supports, we divided the total disbursement initiative by the number of impacted workers to find the value per worker for each initiative. The per-worker value of each initiative was summed up to find the country's total rehiring packages offered per worker.

Once each country's rehiring package total was quantified, low, medium, and high value support packages were determined by dividing country-level

[23] This is estimated from workers data of Indonesia Power coal power plants with capacity ranging from 25 MW to 625 MW. The data can be seen from this link: https://indonesiapower.co.id/reports/statistic-report/statistic-2020-indonesia-power/files/downloads/laporan_statistik_IP_2020.pdf
[24] Source: BPS, August 2021
[25] Authors' calculation using data from two mining company, PT Bukit Makmur Mandiri Utama (BUMA) and PT Kideco (subsidiary of PT Indika Energi)
BUMA: http://deltadunia.com/wp-content/uploads/2021/06/Laporan-Tahunan-PT-Delta-Dunia-Makmur-Tbk-2020.pdf
PT Kideco: https://www.indikaenergy.co.id/wp-content/uploads/2021/04/2020_Annual-Report_English.pdf

supports into three groups and finding the average of each group (Table S7). For example, to find the high estimate, support packages in the countries with the highest identified payments were averaged. To apply this public support package to Indonesia, the low, medium, and high values for rehiring packages were multiplied by the projected number of annual coal power plant job losses to find an estimate of the total potential annual public support. The medium rehiring package (the average of the United States and Canada's average fiscal support per worker) was used for this analysis, though the low and high ranges are also included to show sensitivity.

Our methodology can only calculate mining income losses, not job losses in the mining sector, as we did not calculate the number of mining jobs lost annually. As a result, our analysis discusses social, not fiscal, support for mining jobs. Moving forward, we have a better idea about what is necessary for future analysis of mining job losses, but that data is not available at this time.

Table S6. Cost of the average rehiring package per worker in six countries

Country	Averange Rehiring Package per Worker (USD)	Source
Poland	$7,025	Pogoda (2021)[26]
Spain	$12,739	Gobierno de España (2021)[27]
United States	$15,467	Appalachian Regional Commission (2021)[28]
Canada	$25,316	Support for Albertans (n.d.)[29],Canada-Alberta Job Grant (n.d.)[30],Coal Workforce Transition (2020)[31]
United Kingdom	$34,340	Rising et al. (2021)[32]
Australia	$45,115	World Resources Institute (2021)[33]

Table S7. Low, medium, and high rehiring package ranges (payment per worker)

Rehiring Package Ranges	Low	Medium	High
Amount per Worker (USD)	$9,882	$20,392	$39,727
Total Cumulative Rehiring Support (USD)	$194,920,388	$402,206,680	$783,584,520

[26] Pogoda, A. (2021). Miners from the coal region Eastern Wielkopolska in Poland have ideas for life after coal. Just Transition.
[27] Gobierno de España. (2021). Just Transition Agreements. https://www.transicionjusta.gob.es/Convenios_transicion_justa/common/Folleto_Convenios_Transicion_Justa_EN_uv.pdf
[28] Based on average per-worker rehiring support offered under the POWER Initiative: Appalachian Regional Commission (2021). POWER Project Summaries by State. https://www.arc.gov/wp-content/uploads/2021/09/POWER-Award-Summaries-September-2021.pdf
[29] Support for Albertans affected by coal phase out. https://www.alberta.ca/support-for-coal-workers.aspx
[30] Canada-Alberta Job Grant. https://www.alberta.ca/canada-alberta-job-grant.aspx
[31] Coal Workforce Transition Program: Coal and Electricity Transition Tuition Voucher. (2020).https://www.alberta.ca/fr-CA/assets/documents/ae-coal-workforce-transition-program-guide.pdf
[32] Rising, J., Dumas, M., Dicker, S., Propp, D., Robertson, M. & Look, W. (2021). Regional Just Transitions in the UK: Insights from 40 Years of Policy Experience. RFF & EDF. https://www.edf.org/sites/default/files/documents/UK_Report_Case_Study.pdf
[33] World Resources Institute. (2021). Australia's Latrobe Valley: Coordinating Private COmpanies to Redeploy Power Plant Workers. https://www.wri.org/update/australias-latrobe-valley-coordinating-private-companies-redeploy-power-plant-workers

Public Health Benefits

We evaluated the air quality and public health benefits following the methodology from Myllyvirta (2021)[34]. Our health impacts assessment includes calculations of the avoided number of people affected, avoided deaths, life expectancy reduction, and health costs.

For each plant's air pollutant emission estimates, we used the plant-level data of SO_2, NO_x, PM emissions and followed the emission calculation methodology described in Koplitz et al[35]. The population exposure to PM2.5 pollution is then estimated using the regression model developed by Zhou et al.[36], which takes into account the plant's emission rates, population densities at different distances from the plant and the precipitation rate at the plant location, which affects the deposition of pollutants.

The calculation of health impacts is based on a standard epidemiological equation[37]:

$$\Delta cases = POP \times \sum_{age} \left[Frac_{age} \times Incidence_{age} \times \left(1 - \frac{RR(c_{base} + \Delta c_{coal}, age)}{RR(c_{base}, age)}\right)\right] \quad (3.7)$$

Where POP is the total population in the grid location, age is the analysed age group, $Frac_{age}$ is the fraction of the population belonging to the analysed age group, Incidence is the baseline incidence of the analysed health condition, c is pollutant concentration, with c_{base} referring to the baseline concentration and Δc_{coal} is the concentration attributed to coal-fired power plants, with the contribution from existing plants having a negative sign (subtracted from the baseline concentration) and projected future incremental concentration from new plants a positive sign (added on top of the baseline concentration). RR(c,age) is the function giving the risk ratio of the analysed health outcome at the given concentration, for the given age group, compared with clean air.

In the case of a log-linear, non-age specific concentration-response function, the RR(c,age) function becomes:

$$RR(c) = RR_0^{\frac{c - c_0}{\Delta c_0}} \text{ when } c > c_0\text{, 1 otherwise} \quad (3.8)$$

Where RR_0 is the risk ratio found in epidemiological research, Δc_0 is the concentration change that RR_0 refers to, and c_0 is the assumed no-harm concentration.

The health impacts increase with future population growth, population aging and epidemiological transitions, which are aligned with our socioeconomic projections. We assumed that all plants follow national emissions standards and applied new plant standards to plants commissioned in 2022 or later. Additional assumptions include that all plants with PPAs or permits in Indonesia follow existing plant standards.

We assessed the economic losses from air pollution-related deaths based on the resulting reduction in life expectancy. We adjusted the economic losses by purchasing power adjusted Gross National Income (GNI PPP) with an elasticity of 1.0. The estimates for economic costs per case of each health outcome were calculated as:

$$C_c = C_0 \times \left(\frac{I_c}{I_0}\right)^{\eta} \quad (3.9)$$

Where C_c is cost per case. C_0 is cost at reference income level, I_c is income level, I_0 is the reference income level and η is the elasticity.

The economic cost calculation is based on assumptions that the elasticity of the willingness to pay to avoid health risks with regard to GDP is 1 and the discount rate is equal to the long run GDP growth rate[38].

Results show that the accelerated coal phaseout can avoid 168 (115-228) thousand deaths and save over 60 (40-85) billion$ health costs through 2050 (Figure S6).

[34] https://energyandcleanair.org/hsbc-coal-investments/
[35] Koplitz, S. N., Jacob, D. J., Sulprizio, M. P., Myllyvirta, L., & Reid, C. (2017). Burden of Disease from Rising Coal-Fired Power Plant Emissions in Southeast Asia. Environmental Science & Technology, 51(3), 1467–1476. https://doi.org/10.1021/acs.est.6b03731
[36] Zhou Y et al 2006. The influence of geographic location on population exposure to emissions from power plants throughout China. Environment International 32:365–373. http://dx.doi.org/10.1016/j.envint.2005.08.028
[37] Myllyvirta, L. (2020). Quantifying the Economic Costs of Air Pollution from Fossil Fuels. Centre for Research on Energy and Clean Air. https://energyandcleanair.org/publications/costs-of-air-pollution-from-fossil-fuels/
[38] Viscusi, W. K., & Masterman, C. J. (2017). Income Elasticities and Global Values of a Statistical Life. Journal of Benefit-Cost Analysis, 8(2), 226–250. https://doi.org/10.1017/bca.2017.12

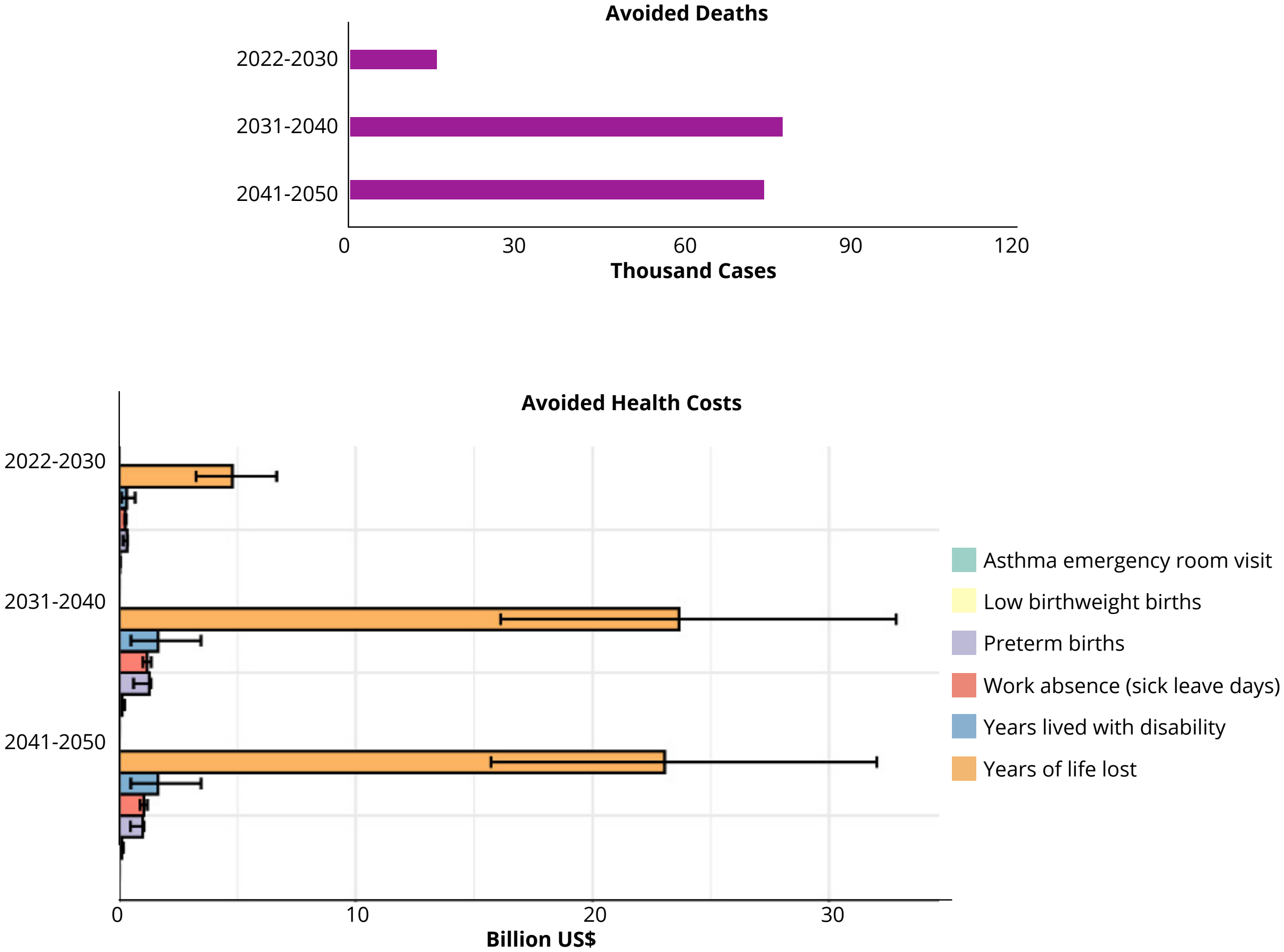


Figure S6. Deaths and health costs avoided by rapid coal phaseout

Metrics Not Quantified

Due to limits in data availability, we were unable to quantify all of the metrics that were identified in the social dimension. The following metrics were not quantified:

- **Fiscal support for job losses (supply chain):** Worker layoffs and income loss along the entire supply chain (e.g. coal mine and transport).
- **Green job growth:** Number of new green jobs created and changes in income.
- **Human development:** Improved environmental justice and human capital with better health and jobs.
- **CFPP support to the surrounding community:** The availability of corporate social responsibility funds from the coal power plant owners for public facilities and surrounding communities.

S3.3. Environmental Outcomes

GHG Emissions Reductions

CO_2 emissions from coal power plants are reduced in our 1.5°C- compatible scenario compared to the BAU scenario (Figure S6). By 2030, cumulative emissions reductions from today reach 341 $MtCO_2$ and by 2050, they reach 2,485 $MtCO_2$.

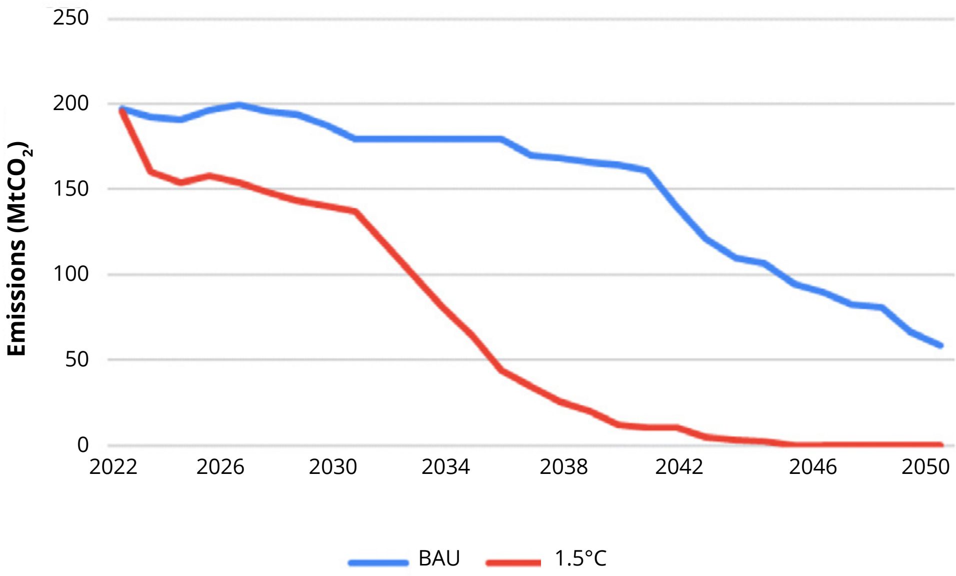


Figure S7. CO_2 emissions pathway through 2050 under 1.5°C and BAU scenarios

Metrics Not Quantified

Due to limits in data availability, we were unable to quantify all of the metrics that were identified in the environmental dimension. The following metrics were not quantified:

- **Avoided air pollution control retrofit cost:** Cost savings from avoided retrofit and OPEX cost for air pollution control equipment for the retired CFPP (based on Republic of Indonesia Ministry of Environment and Forestry regulation 15/2019).
- **Reclamation cost:** Costs to restore and rehabilitate coal mining sites.
- **Water savings and water quality:** Water savings and cost savings from avoided water pollution treatment and groundwater pollution from retired CFPP.

S4. Energy Investment

Our energy investment calculation includes electricity, transmission and energy efficiency investments. We quantified these investments by using projected capacity from the GCAM model, overnight capital costs by technology, and investment assumptions from existing literature.

To calculate electricity investment, annual capacity additions are multiplied by the capital cost of each technology (Equation 4.1; see Table S8 for cost assumptions).

To calculate transmission investment, regional 2020 electricity investments are multiplied by the model average share of global transmission investment relative to electricity investment from McCollum et al. 2018. Then, the 2020 regional values are multiplied by the ratio of electricity investment in each time period relative to 2020 (Equation 4.2 and 4.3; see Table S8 for cost assumptions).

To calculate energy efficiency investment, regional shares of electricity investment are multiplied by the model average energy efficiency investment from McCollum et al. 2018[39] (Equation 4.4; see Table S8 for cost assumptions).

$$Electricity\ investment_i = capacity\ additions\ x\ capital\ cost$$

(4.1)

Where i indicates each individual technology

$$2020\ transmission\ investment_r = 2020\ EI_r \times \left(\frac{2020\ TI}{2020\ EI}\right)_{g,m}$$

(4.2)

Where EI indicates electricity investment, r indicates Indonesia's value, TI indicates transmission investment, g indicates global value, and m indicates model average.

$$Future\ transmission\ investment_{r,t} = \frac{EI_{r,t}}{2020\ EI_{r,t}} \times 2020\ TI_r$$

(4.3)

Where r indicates Indonesia's value, t indicates each GCAM time period, EI indicates electricity investment, and TI indicates transmission investment.

$$Energy\ Efficiency\ Investment_{r,t} = \frac{EI_r}{EI_g} \times EE_{g,m}$$

(4.4)

Where r indicates Indonesia's value, t indicates each GCAM time period, EI indicates electricity investment, EE indicates energy efficiency investment, g indicates global value, and m indicates model average.

[39] D. L. McCollum et al., Nat Energy. 3, 589–599 (2018).

Table S8. Capital cost assumptions used for power system technologies in Indonesia[40]

Capital Cost Assumptions (2019$/KWe)				
Subsector	**Technology**	**2020**	**2030**	**2050**
Solar	PV	790	560	410
	rooftop_pv	1320	940	690
	PV_storage	2625	1682	1247
	CSP_storage	4157	3019	2164
Wind	wind	1500	1280	1080
	wind_offshore	3500	2980	2520
	wind_storage	4530	3400	2673
Geothermal	geothermal	4000	3440	2840
Biomass	small plant	2000	1820	1600
Gas	gas (CC CCS)	1150	970	750
	gas (CC)	556	488	410
	gas (steam/CT)	475	415	347
Coal	subcritical	1650	1600	1550
	supercritical	1400	1360	1320
	ultra-supercritical	1520	1480	1430

In this study, we calculated energy investments based on certain assumptions about technologies and power system dynamics. However, there is a great deal of uncertainty around how the energy system will evolve in the future, which would lead to different sets of investment needs. In Figure S8, we compare our electricity generation data with the data in IESR's deep decarbonization report (2021)[41]. These projections about electricity generation in Indonesia lead to different investment needs, as shown in Figure S9.

[40] The Directorate General of Electricity (2021). Technology Data for the Indonesian Power Sector. Retrieved from https://www.ea-energianalyse.dk/en/publications/technology-data-for-the-indonesian-power-sector/
[41] Institute for Essential Services Reform (2021). Deep Decarbonization of Indonesia's Energy System: A Pathway to Zero Emissions by 2050. Retrieved from https://iesr.or.id/download/deep-decarbonization

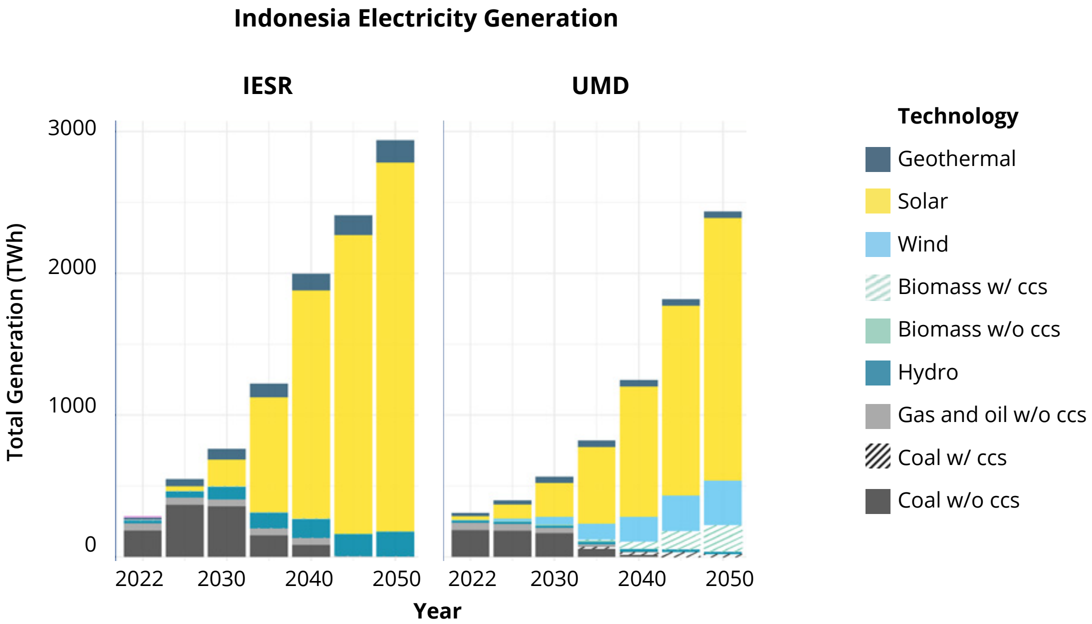


Figure S8. Electricity generation by technology through 2050, comparing IESR's deep decarbonization report (2021) versus this study

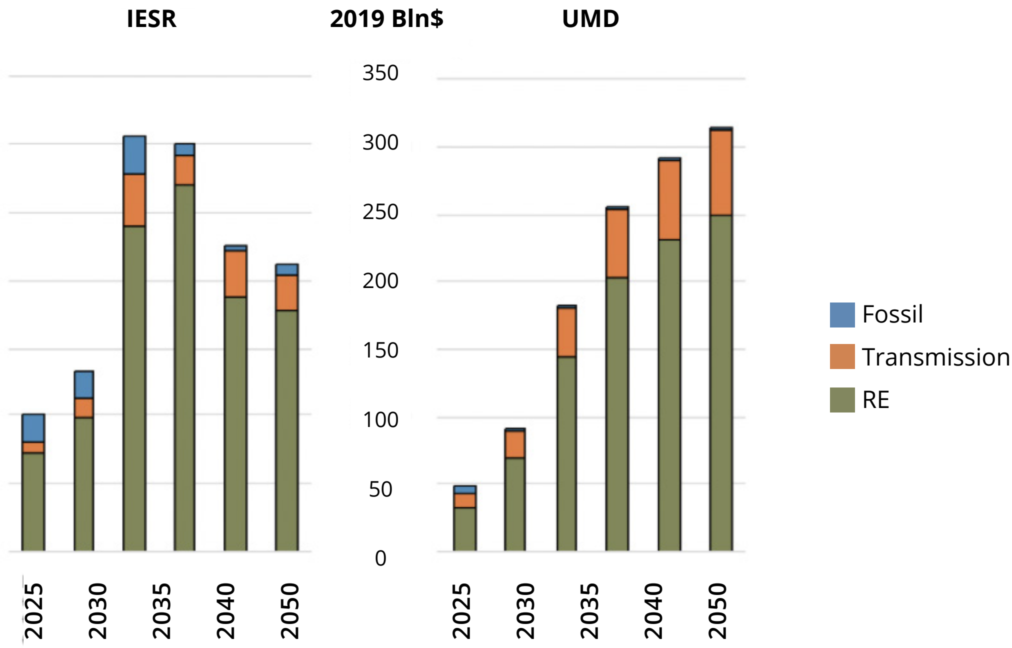


Figure S9. Energy investments through 2050, comparing IESR's deep decarbonization report (2021) versus this study.

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