Health Benefits of Just Energy Transition and Coal Phase-out in Indonesia

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About CREA

The Centre for Research on Energy and Clean Air (CREA) is an independent research organisation focused on revealing the trends, causes, and health impacts, as well as the solutions to air pollution. CREA uses scientific data, research, and evidence to support the efforts of governments, companies, and campaigning organisations worldwide in their efforts to move towards clean energy and clean air, believing that effective research and communication are the keys to successful policies, investment decisions, and advocacy efforts. CREA was founded in Helsinki and has staff in several Asian and European countries.

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Key findings

- Air pollutant emissions from coal power plants increased by 110% in Indonesia over the past decade. If all planned coal power plants, including captive power plants, are completed and put into operation, a further 70% increase is expected under the current policies scenario by 2030.

- Detailed air quality and health impact modelling carried out for this report indicate that air pollutant emissions from coal-fired power plants in Indonesia in 2022 were responsible for 10,500 deaths from air pollution (95% CI: 6,500–16,400) and health costs of USD 7.4 billion (IDR 109.9 trillion; 95% CI: USD 4.6–11.5 billion, IDR 67.6–170.3 trillion).

- Current policies would increase Indonesia's current coal-fired capacity of 45 GW to 63 GW, before peaking in 2028. This would result in deaths linked to air pollution from coal power rising to 16,600 per year (95% CI: 10,300–25,900) and health costs to USD 11.8 billion per year (IDR 175.2 trillion; 95% CI: USD 7.2–18.2 billion, IDR 106.9–270.3 trillion).

- Under current policies, cumulative health impacts from 2024 until the end of life of all coal power plants would result in 303,000 air-pollution-related deaths (95% CI: 189,000–468,000) and health costs of USD 210 billion (IDR 3.2 quadrillion; 95% CI: USD 130–330 billion, IDR 2.0–4.9 quadrillion).

- A faster coal phase-out by 2040, in line with the 1.5 degrees target of the Paris Agreement, would avoid a cumulative total of 182,000 air pollution-related deaths (95% CI: 114,000–280,000) and health costs of USD 130 billion (IDR 1,900 trillion; 95% CI: USD 80–200 billion IDR 1,200–2,900 trillion), from 2024 until the end-of-life of all plants.

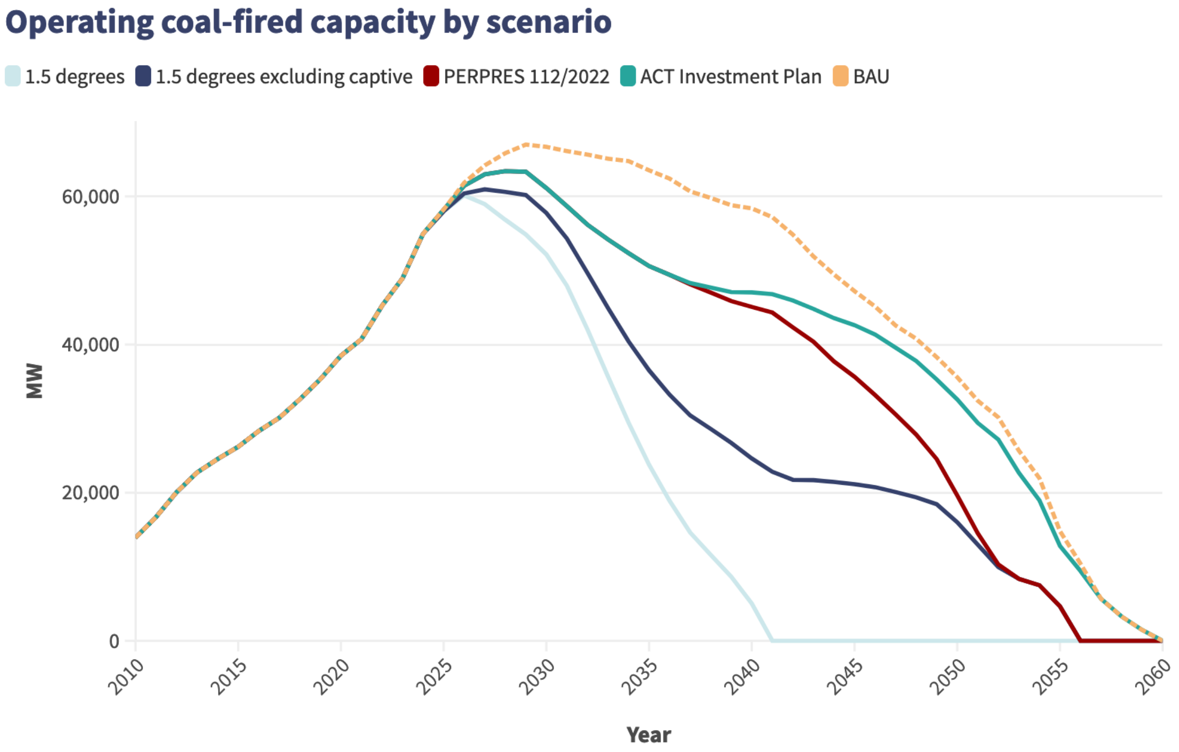
- Mandatory air pollution controls installation would avoid 8,300 air pollution-related deaths in 2035 in the current policies scenario (95% confidence interval: 5,200–12,600), as well as health costs of USD 5.8 billion (IDR 86.5 trillion; 95% CI: USD 3.6–8.9 billion, IDR 54.1–131.5 trillion).

- Cumulative avoided health costs would reach USD 90 billion (IDR 1.3 quadrillion; 95% CI: USD 60–140 billion, IDR 0.8–2.0 quadrillion), yielding a net economic benefit of USD 70 billion (IDR 290 trillion) to the society, considering the investment and operating costs of the air pollution controls, making the investments highly profitable from a social point of view.

- Responsible for one-fifth of all health impacts of coal-fired plants in Indonesia, it is crucial to include captive coal power plants in the Energy Transition Mechanism (ETM) and Just Energy Transition Partnership (JETP) to make meaningful progress. Excluding them from the 2040 coal phase-out policy could cause an additional health burden of 27,000 air pollution deaths. (95% CI: 16,000–42,000) and health costs of USD 20 billion (IDR 330 trillion; 95% CI: USD 10–30 billion, IDR 200–520 trillion).

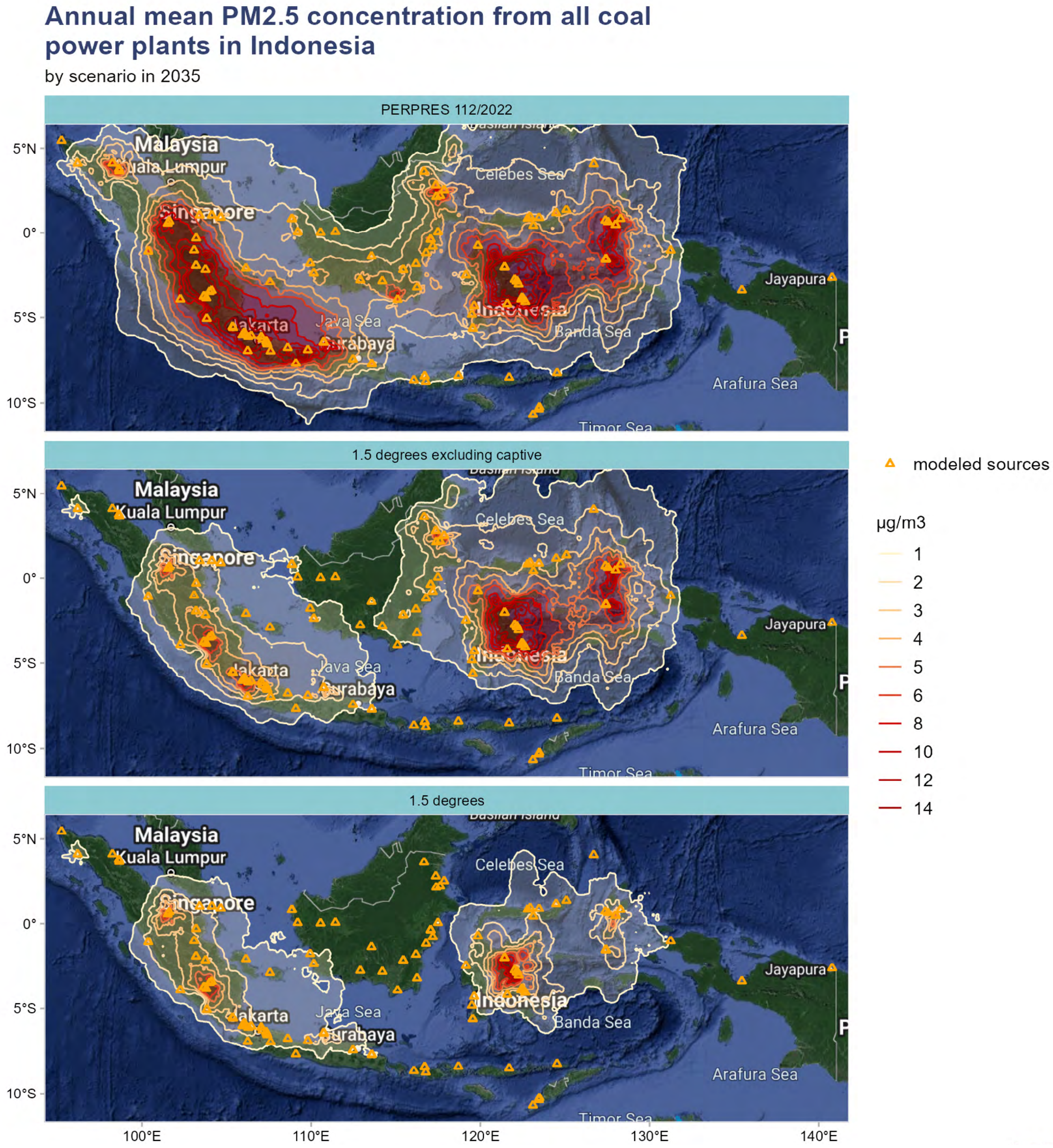
- We also assessed the impacts of current and planned biomass co-firing on air pollution from coal power plants. Raising the share of co-firing to a minimum of 20% at all PLN (*Peraturan Listrik Negara*, Indonesia's state-owned electricity provider) power plants — a significant challenge in terms of the availability of biomass and potentially also a technical challenge — would merely reduce the emissions of air pollutants from Indonesia's coal power plants by 1.5–2.4% depending on the pollutant.

- Reduction of air pollution from coal power plants can only be effectively achieved through the proper installation of emission control technology. CREA's analysis shows that having air pollution control installed in all operating coal power plants beyond 2035 would reduce the emissions of SO_x by 73%, NO_x by 64%, dust by 86%, and mercury by 71%. Ammonia co-firing would worsen air quality impacts due to fugitive ammonia emissions.



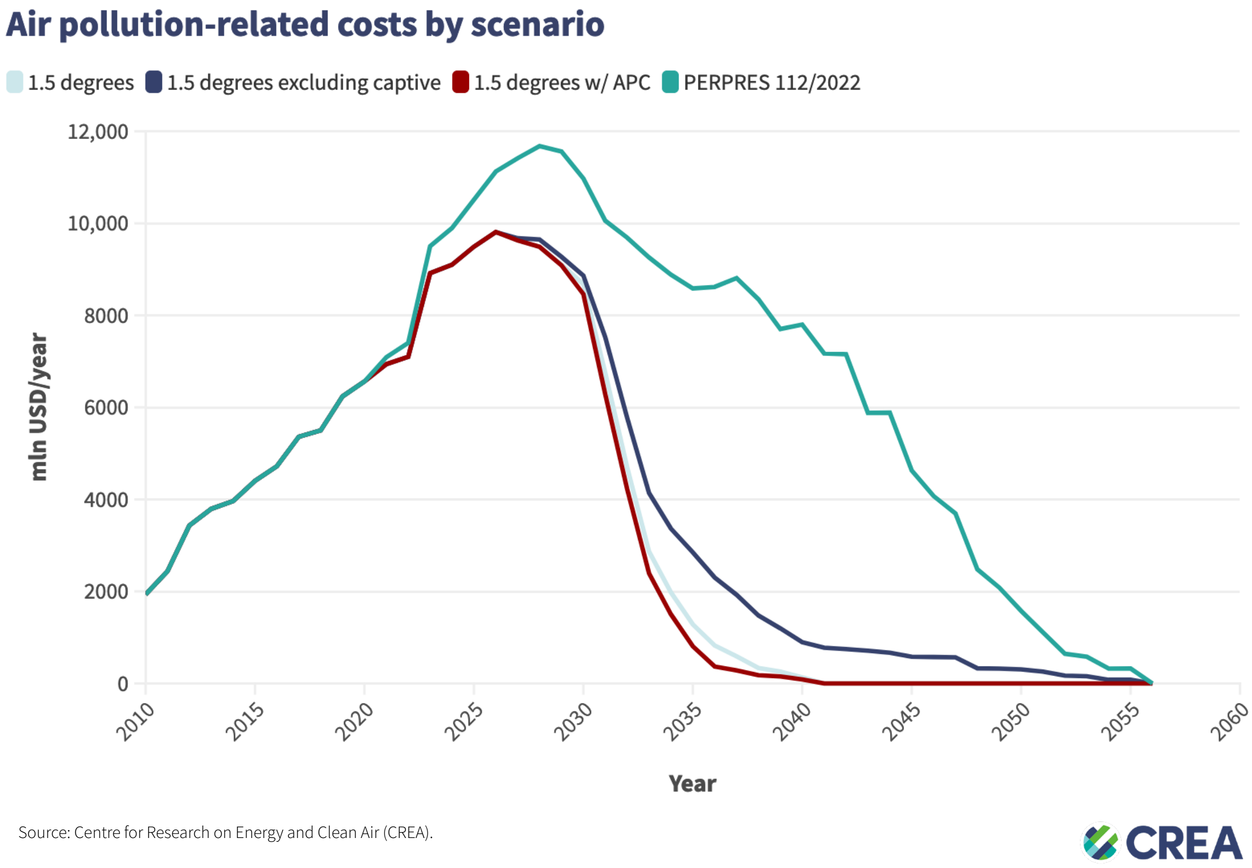
Source: Centre for Research on Energy and Clean Air (CREA) analysis based on University of Maryland and Global Energy Monitor (GEM) data.

KF 1. Operating coal-fired capacity by scenario



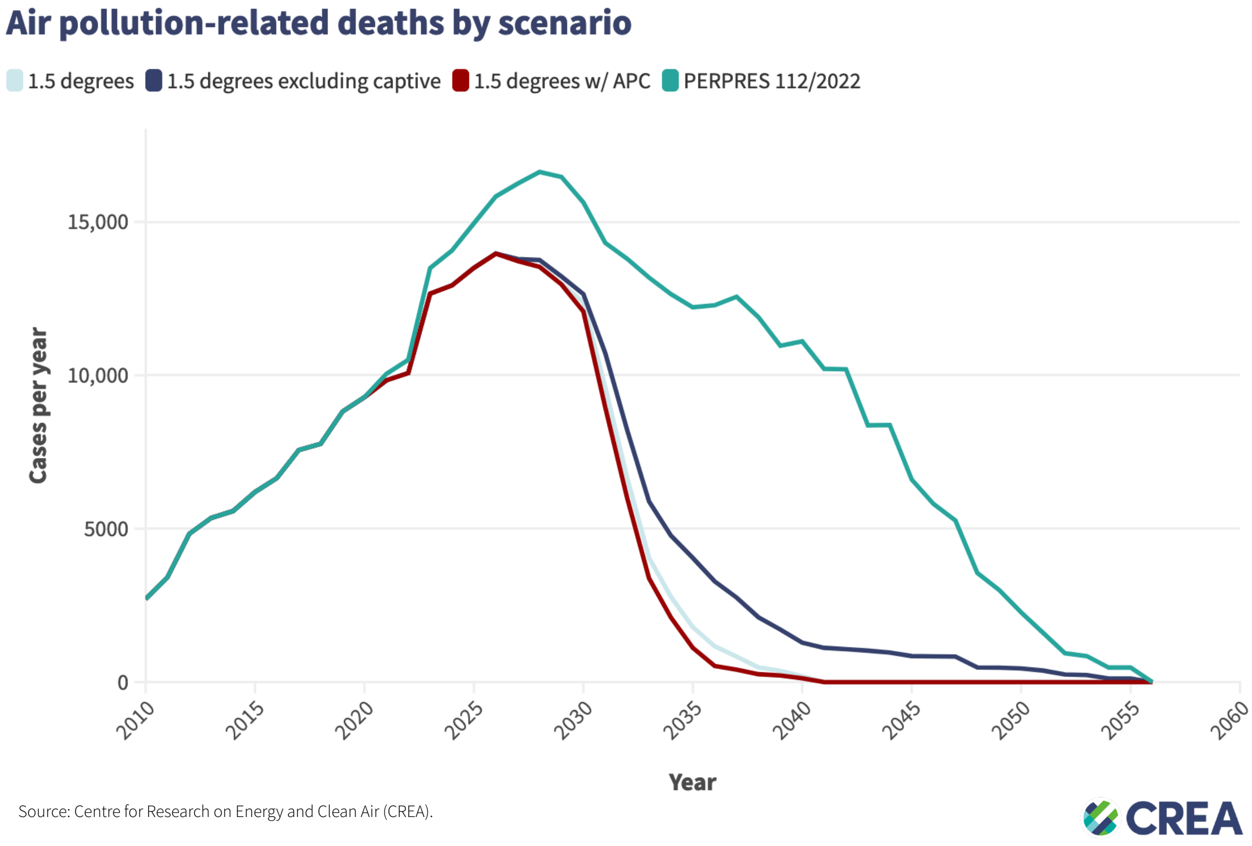
Source: Centre for Research on Energy and Clean Air (CREA).

KF 2. Annual mean $PM_{2.5}$ concentration from all coal power plants in Indonesia


Air pollution-related costs by scenario

Source: Centre for Research on Energy and Clean Air (CREA).

KF 3. Air pollution-related annual costs by scenario


Air pollution-related deaths by scenario

Source: Centre for Research on Energy and Clean Air (CREA).

KF 4. Air pollution-related annual deaths by scenario

Contents

Abbreviations

1.5 degrees	Target threshold limit of 1.5°C above pre-industrial levels agreed in the 2015 Paris Agreement
ACT	Accelerating Coal Transition
ADB	Asian Development Bank
APC	Air Pollution Control
AQLI	Air Quality Life Index
ASEAN	Association of Southeast Asian Nations
CCS	Carbon Capture and Storage
CEMS	Continuous Emission Monitoring System
CFPP	Coal-fired Power Plant
CI	Confidence Interval
CIF	Climate Investment Funds
CO	Carbon Monoxide
CO2	Carbon Dioxide
EEA	European Environment Agency
EIA	Environmental Impact Assessment
ETM	Energy Transition Mechanism
FGC	Flue Gas Concentration
GCPT	Global Coal Plant Tracker
GDP	Gross Domestic Product
GEM	Global Energy Monitor
GNI PPP	Gross National Income in Purchasing Power Parity
GW	Gigawatt
$GtCO_2$-eq	Gigatonnes of carbon dioxide equivalent
H_2O_2	Hydrogen Peroxide
IEA	International Energy Agency
IEEFA	Institute for Energy Economics and Financial Analysis
IESR	Institute for Essential Services Reform
IHME	Institute for Health Metrics and Evaluation
int. USD	International Dollar, equivalent to the purchasing power of 1 USD
IPP	Independent Power Producer
JETP	Just Energy Transition Partnership
LCCP	Low Carbon Scenario Compatible with Paris Agreement
LHV	Lower Heating Value
LTS-LCCR 2050	Long-Term Strategy for Low Carbon and Climate Resilience 2050
MEMR	Ministry of Energy and Mineral Resources
$\mu g/Nm^3$	Microgram per normal cubic metre (at 101.325 kPa, 273.15 K)

mg/Nm^3	Milligram per normal cubic metre (at 101.325 kPa, 273.15 K)
$MtCO_2$-eq	Million tonnes of carbon dioxide equivalent
MW	Megawatt
NDC	Nationally Determined Contribution
NH_3	Ammonia
Nm^3/GJ	Normal cubic metre per GigaJoule (at 101.325 kPa, 273.15 K)
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
O_3	Ozone, ground-level
OECD	Organisation for Economic Co-operation and Development
PERPRES 112/2022	*Peraturan Presiden No. 112 Tahun 2022 tentang Percepatan Pengembangan Energi Terbarukan untuk Penyediaan Tenaga Listrik*, Presidential Regulation No. 112 Year 2022 on the Acceleration of the Development of Renewable Energy for the Provision of Electric Power
PLN	*Perusahaan Listrik Negara*, Indonesia’s State-owned Electricity Provider
PM	Particulate Matter
$PM_{2.5}$	Particulate Matter with particles that are 2.5 microns or less in diameter
PM_{10}	Particulate Matter with particles that are 10 microns or less in diameter
PPA	Power Purchase Agreement
RUPTL	*Rencana Umum Usaha Penyediaan Tenaga Listrik,* PLN’s 10-year business plan
SO_2	Sulphur Dioxide
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USD	The United States Dollar
WRF	Weather Research Forecasting

Executive Summary

Background and methodology

Indonesia relies on coal-fired power for 62.5% of its electricity generation (PLN, 2022). This reliance comes with significant impacts on the country's air quality and public health, as well as a major contribution to the growth in greenhouse gas emissions over the past decade. The coal phase-out and net-zero pathways currently being prepared are a major opportunity to clean up Indonesia's power system. This study assesses the current air quality and its health impacts, and the associated external economic costs of coal power plants in Indonesia. The study also includes the impact of various policy pathways into the future. We present the first health-based phase-out pathways that are designed to maximise public health benefits of retiring coal power plants.

By using the impact pathway approach, this study quantifies the health impacts of air pollutant emissions from coal power generation in Indonesia. This approach is the most common way to study the health impacts of air pollutant sources. This approach includes following the chain of causation from emissions, to atmospheric dispersion and chemical transformation, population exposure, resulting health impacts, and the economic cost of those health impacts. The impacts are quantified for the pathway implied by the regulation currently in place, for the 1.5-degree-aligned pathway for utility power plants, and for the 1.5-degree-aligned pathway for both captive and utility power plants. The study also quantifies the impact of more stringent air pollutant emission controls and different levels of biomass co-firing.

The analysis is done by developing a plant-by-plant inventory of emissions, estimating plant-level pollution dispersion through atmospheric modelling, quantifying health impacts resulting from changes in ambient concentration, and valuing health impacts in monetary terms using economic costs per case of different health outcomes compiled from literatures and transferred to Indonesia's level of income and GDP per capita.

The emission inventory is based on disclosures by plant operators as far as possible, with the plant-specific data compiled for as many plants as possible and generalised to other plants of the same type. We assume that all power plants meet the national emissions standards, providing conservative estimates of impacts. Future health and economic impacts are projected taking into account population growth, economic growth, and projected changes in demographics.

Current impacts of coal power emissions

Based on the estimations of the Air Quality Life Index (AQLI), 91% of Indonesia's population is exposed to air pollution levels worse than WHO guidelines. In the most polluted province, West Java, air pollution reduces the life expectancy of its 48 million residents by 4.1 years. Comparably, the residents of the Jakarta Metropolitan Area, Jabodetabek, are exposed to high levels of particulate pollution, and life expectancy is 5.5 to 6.4 years shorter than those living in regions where WHO guidelines are met (AQLI, 2022).

According to a 2015 study conducted by the Atmospheric Chemistry Modeling Group of Harvard University and Greenpeace Southeast Asia, air pollution emitted by coal-fired power plants (CFPP) was estimated to be responsible for 6,500 premature deaths annually in 2011 (Koplitz et al., 2017). For each new addition of a 1,000 MW power plant, an average of 600 Indonesian adults and children would be severely impacted by acute and chronic respiratory diseases due to exposure to fine particulate matter and gaseous pollutants (Greenpeace Indonesia, 2015).

Air pollutant emissions from coal power in Indonesia have increased by an estimated 110% over the past decade. Under the current policy, the emissions are expected to further increase by 70% by 2030. In 2022, emissions from coal plants were responsible for 10,500 deaths (95% CI: 6,500–16,400) and health costs of USD 7.4 billion (IDR 109.9 trillion; 95% CI: USD 4.6–11.5 billion, IDR 67.6–170.3 trillion). However, under the current policy, the deaths linked to emissions from coal-fired power plants are estimated to rise to 16,600 a year (10,300–25,900), while the health costs would accordingly rise to USD 11.8 billion per year by the end of the decade (IDR 175.2 trillion; 95% CI: USD 7.2–18.2 billion, IDR 106.9–270.3 trillion).

Future impacts under different retirement pathways

After evaluating the air quality and health impacts of all coal power plants in Indonesia, we projected future emissions and health impacts for different pathways. Our "current policies" pathway is based on PERPRES 112/2022, which requires all PLN and IPP power plants and new captive power plants to retire by 2050. In addition, we assume that all existing captive power plants would retire after 30 years of operation while emission standards for all plants remain unchanged at the current level. Under this scenario, starting from 2024 until the end-of-life of all coal-fired power plants in Indonesia, coal power emissions would lead to the cumulative amount of 303,000 air-pollution-related deaths (95% CI: 189,000–468,000) and health costs of USD 210 billion (IDR 3.2 quadrillion; 95% CI: USD 130–330 billion, IDR 2.0–4.9 quadrillion).

As an alternative, we evaluate the 1.5 degrees pathway, aligned with the goals of the Paris Agreement and the International Energy Agency's recommendation to phase out coal power plants by 2040. Compared with current policies, this faster coal phase-out would avoid a cumulative total of 182,000 air pollution-related deaths (95% confidence interval: 114,000–280,000) and health costs of USD 130 billion (IDR 1,900 trillion; 95% CI: USD 80–200 billion IDR 1,200–2,900 trillion), from 2024 until the end-of-life of all plants.

Indonesia's current air pollutant emissions standards for coal-fired power plants are far behind best international practices and best available technology. This is clear from comparisons with e.g. China, South Korea, and the European Union. We, therefore, model a pathway in which all power plants that are expected to operate beyond 2035 are mandated to install efficient emission control devices by 2030. In this pathway, 8,300 air pollution-related annual deaths could be avoided in 2035 in the current policies scenario (95% confidence interval: 5,200–12,600), as well as health costs of USD 5.8 billion (IDR 86.5 trillion; 95% CI: USD 3.6–8.9 billion, IDR 54.1–131.5 trillion). The cumulative avoided health costs would reach USD 90 billion (IDR 1.3 quadrillion; 95% CI: USD 60–140 billion, IDR 0.8–2.0 quadrillion), yielding a net economic benefit of USD 70 billion (IDR 290 trillion) to society, considering the investment and operating costs of the air pollution controls, making the investments highly profitable from a social point of view.

From the greenhouse gas and public health perspective, it is essential to include captive power plants in Indonesia's coal phase-out policies as these plants are responsible for approximately 20% of the total health impacts of coal-fired power in the country. Excluding captive power plants from a 2040 coal phase-out policy could cause an additional health burden of 27,000 air pollution-related deaths (95% confidence interval: 16,000–42,000) and health costs of USD 20 billion (IDR 330 trillion; 95% CI: USD 10–30 billion, IDR 200–520 trillion). Even as the coal phase-out begins, some power plants are expected to operate well into or beyond the 2030s. Investing in improved air pollution controls in those power plants would deliver substantial health and economic benefits.

PLN's plans for meeting renewable energy targets set for 2025 and 2030 rely heavily on biomass co-firing. Our evaluation of co-firing on air pollutant emissions and health impacts from coal power revealed it to be very modest. Raising the share of this co-firing to a minimum of 20% at all PLN power plants would reduce these emissions by 1.5 to 2.4%, depending on the pollutant. In contrast, requiring efficient emission control technology at all power plants operating beyond 2035 would reduce emissions of SO_x by an estimated 73%, NO_x by 64%, dust by 86%, and mercury by 71%.

There are also tentative plans for co-firing ammonia at some coal power plants. Besides the likely practical and economic unviability of the idea, it could worsen air quality impacts, due to fugitive ammonia emissions from the transportation and handling of ammonia and from the power plant itself.

Benefits of health-based coal power plant retirement

Power plants located near densely populated areas have the highest public health costs. The impact on the population is exacerbated by several factors, including unfavourable wind patterns and poor emission control measures. Clear examples of this correlation include PLN Muara Karang and Lontar power plants located in Jakarta and Tangerang, as well as the captive coal power plants located in Bekasi, Karawang, Purwakarta, and Bandung.

The health benefits and cost-effectiveness of the coal phase-out are maximised by prioritising the plants with the highest health impacts in the order of retirement. If we followed the simple logic of retiring the oldest plants first, the number of air pollution-related deaths in the current policies scenario would be 36,000 cases higher. Simultaneously, the health costs would increase by USD 24 billion (IDR 360 trillion) — by as much as 12%. Under the 1.5 degrees scenario, implementing an age-based retirement schedule would cause additional cumulative air pollution-related cost burdens of USD 12 billion (IDR 180 trillion).

Introduction

Indonesia is the largest emerging economy in Southeast Asia — having the 4th largest population in the world and maintaining an average GDP growth rate of 5.3% in the 2011-2019 period before the COVID-19 pandemic hit in 2020 (World Bank Open Data, 2023a). The final energy consumption grew at an average rate of 3.0% over the same period. Indonesia experienced a reduction in energy consumption in 2020 and 2021 as a result of the pandemic but quickly rebounded in 2022 as economic activities resumed (MEMR, 2023a).

Exporting 494 million tonnes of coal, or about 70% of its national production, Indonesia contributes 21% of global coal exports by monetary value (MEMR, 2023b; Workman, 2022). Indonesia's coal resources and reserves are mainly medium-quality coal distributed over East Kalimantan and low-quality coal over Central and South Sumatra (IESR, 2019).

Despite the presence of recoverable oil and natural gas reserves of 25 billion barrels of oil equivalent, Indonesia is faced with challenges in maintaining domestic output levels and meeting rising demand. Indonesia is already a net importer of oil and is projected to become a net importer of natural gas by 2030 (McKinsey & Company, 2020). Indonesia has been relying on fossil fuels for the nation's energy needs, where coal, oil, and gas made up nearly 88% of the national primary energy supply in 2022 — at 42%, 32%, and 14%, respectively. Renewable energy, with a 12% share, has remained vastly untapped (MEMR, 2023a).

As the urbanisation rate significantly increases parallel to economic development — reaching 57% in 2021 (World Bank Open Data, 2023b), Indonesia's major metropolitan areas are faced with negative environmental consequences driven by urban consumption patterns. Higher energy consumption for electricity, transportation, and cooking in urban areas directly results in higher pollution release to air, water, and soil, due to the high reliance on fossil fuels and biomass. Indonesia is also among the countries most vulnerable to the impacts of climate change, classified in the top-third risk grouping (48 out of 191) in the 2023 INFORM Risk Index mainly due to high exposure risk to floods, earthquakes, and droughts (European Commission, 2023).

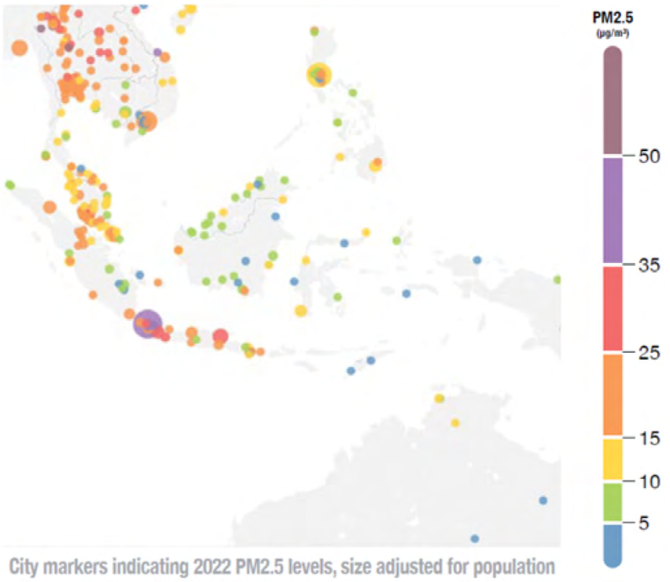
To express its national commitment to tackling climate change, Indonesia ratified the Paris Agreement in 2016, through the Nationally Determined Contribution pledged for 2020–2030. In the latest strengthened commitment published in 2022, Indonesia submitted the Enhanced NDC to the United Nations Framework Convention on Climate Change (UNFCCC) Secretariat, in which the emission reduction target is increased from 29% to 31.89% unconditionally with the country's own effort, and from 41% to 43.20% conditionally with international support (UNFCCC, 2022).

The Enhanced NDC is aimed to be aligned with the Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR 2050) (UNFCCC, 2021), to help the country transition towards the Second NDC and realise Net Zero Emissions by 2060 or sooner. The LTS-LCCR 2050 is designed to strengthen Indonesia's One Hundred Years Vision, "Visi Indonesia 2045" (Kementerian PPN/Bappenas, 2019), in which ambitious targets for human resource development, sustainable economy, equitable development, and consolidation of national resilience and governance are defined.

Under the Low Carbon Scenario Compatible with Paris Agreement (LCCP) scenario included in LTS-LCCR 2050 set to be in line with the 1.5 degrees target, national emissions are projected to reach their peak in 2030 at 1.24 $GtCO_2$-eq. Post 2030, emissions are projected to gradually decline at a rate of around 30.7 $MtCO_2$-eq annually, to reach 0.54 GtCO2-eq in 2050 or equivalent to 1.61 ton of CO_2-eq per capita. To achieve these targets, Indonesia must achieve a net sink in Forestry and Other Land Uses (FOLU) by 2030, while also focusing on the energy sector development and transformation. Particularly for power generation, the LCCP scenario projects shifts away from coal, enhancement of renewables share, and integration of biomass-coal co-firing power plants are connected to CCS.

A concrete transition strategy is essential, not only to mitigate climate risks but most importantly to anticipate the consequences of development and industrial growth. Energy generation-related air pollution has severe impacts on health. Air pollution disproportionately impacts low- and middle-income countries, with Southeast Asia and Western Pacific countries facing the greatest burden, according to WHO (WHO, 2021). Indonesia faces growing issues of pollution and environmental degradation as economic activities have significantly increased over the past decades.

Air Quality Life Index (AQLI) estimates that 91% of Indonesia's population is exposed to air pollution levels above the WHO guidelines. Air pollution in West Java, ranked as the most polluted province, reduces the life expectancy of its 48 million residents by 4.1 years. The residents of the Jakarta Metropolitan Area, Jabodetabek, are exposed to high levels of particulate pollution, and life expectancy is 5.5 to 6.4 years shorter than those living in regions where WHO guidelines are met (AQLI, 2022).



Source: IQAir.

Figure 1. $PM_{2.5}$ Concentration Distribution Map over Indonesia (IQAir, 2022)

The distribution of $PM_{2.5}$ levels across the monitored major cities in Indonesia is visualised in IQAir's 2022 World Air Quality report, where Indonesia ranks worst in the Southeast Asian region and Jakarta is shown to have the worst annual average of $PM_{2.5}$ concentration of 36.2 $\mu g/m^3$ (IQAir, 2022). Noting most areas in the island of Java, where 56% of Indonesia's population resides, show annual exposure exceeding three to seven times the WHO's guideline for annual $PM_{2.5}$ concentration threshold of 5 $\mu g/m^3$ (BPS, 2023).

Coal-fired power plants are one of the major sources of air pollutant emissions, and a significant cause of growth in emissions. According to a study conducted by the Atmospheric Chemistry Modeling Group of Harvard University and Greenpeace Southeast Asia in 2015, air pollution emitted by coal-fired power plants (CFPP) was estimated to be responsible for 6,500 premature deaths annually in 2011 (Koplitz et al., 2017). For each new addition of a 1,000 MW power plant, an average of 600 Indonesian adults and children would be severely impacted by acute and chronic respiratory diseases due to exposure to fine particulate matter and gaseous pollutants (Greenpeace Indonesia, 2015).

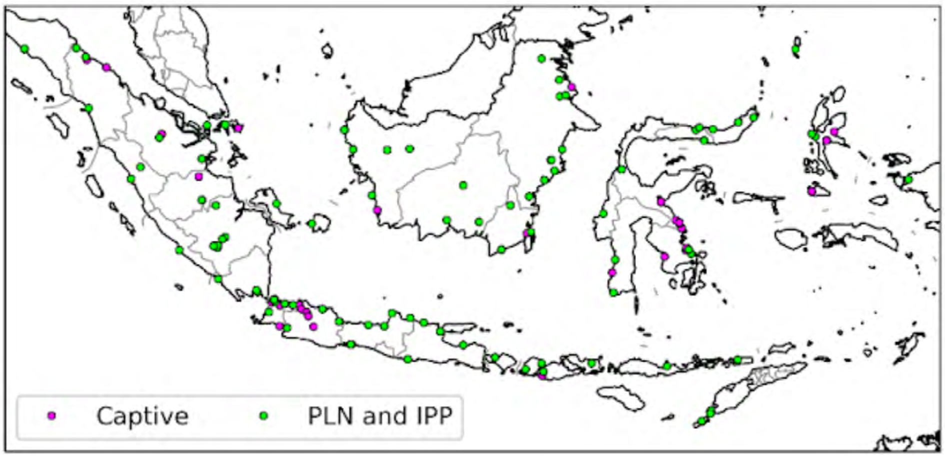
A commentary released by Satya Widya Yudha, a member of the National Energy Council, highlights air pollution impacts of forest fires and peatland degradation, coal-fired power plants, and vehicle emissions, and emphasises the need for legal reforms to mitigate the human cost of air pollution, namely increased cases of upper respiratory infections and premature deaths (NBR, 2018).

Indonesia has to prioritise the adoption of cutting-edge energy-efficiency and clean energy solutions to avoid these risks, by phasing out the oldest and major CFPP emitters.

State of coal-fired electricity generation

In Indonesia, electricity production and distribution is handled by the national government through the state-owned PT Perusahaan Listrik Negara (PLN) and its subsidiaries, with Independent Power Producers (IPP) responsible for a significant share of generation. The total installed capacity in the country is 69,040 MW, of which PLN operates 6,314 units with a combined capacity of 44,940 MW, or about 65%. The remaining 24,100 MW (35%) is operated by IPPs, according to PLN's 2022 Statistical Report (PLN, 2022).

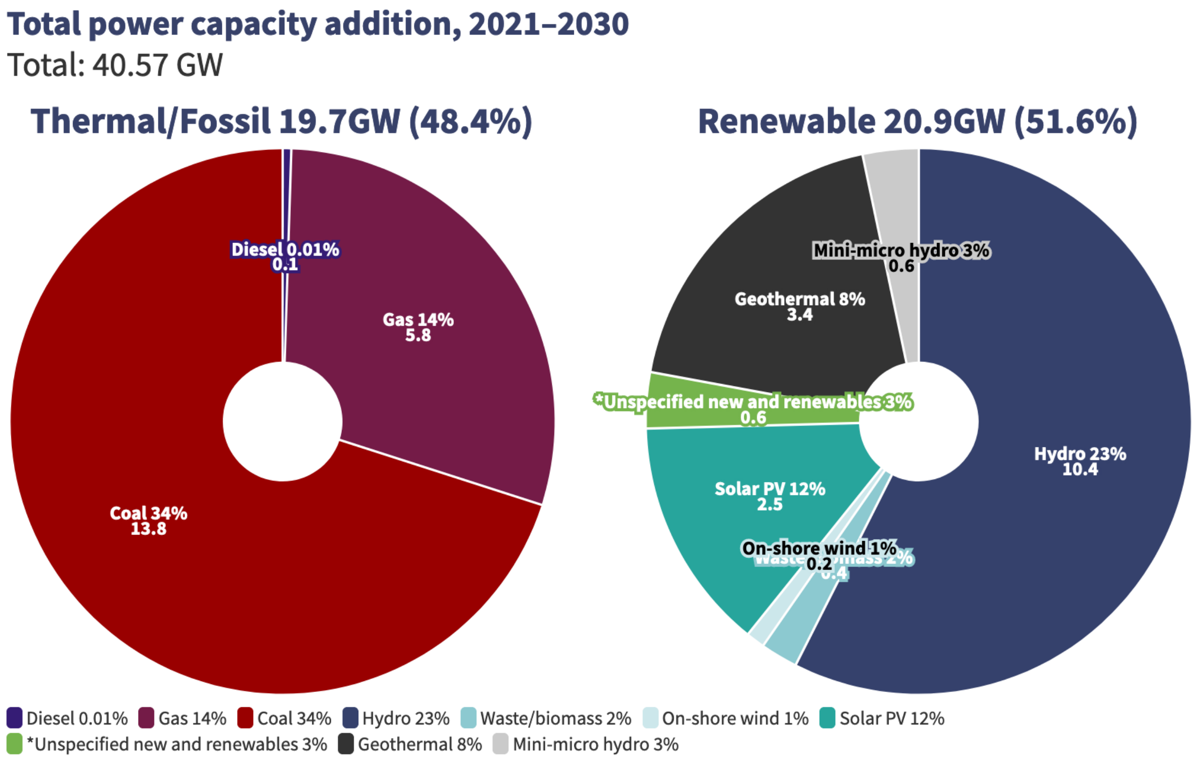
Indonesia has been reliant on fossil fuels, particularly coal for power generation. Coal is the primary fuel source for power generation at 62.5% share in 2022, followed by natural gas at 22.2% and oil at 5.6%, and the remaining 9.7% from renewables (PLN, 2022). Figure 2 below provides the locations of the CFPPs across the country, showing PLN and IPP power plants for the national electricity supply, and captive power plants dedicated to energy-intensive industrial parks located in East and Central Java, North Sumatra, Sulawesi, and Maluku.



Source: Centre for Research on Energy and Clean Air (CREA),
Global Energy Monitor (GEM).

Figure 2. Indonesia's coal power capacity distribution (CREA, 2023; GEM, 2022)

In October 2021, PLN released the company's 10-year business plan, *Rencana Umum Usaha Penyediaan Tenaga Listrik* (RUPTL) 2021–2030. The document outlines a plan to add a total of 40,575 MW power generation capacity by 2030, where 51.6% comes from renewables, and 48.5% comes from fossil fuels (MEMR, 2021; OECD, 2021). The breakdown is illustrated in Figure 3.



Source: RUPTL 2021-2030. *This category includes power generated from new and renewable energy sources to supply baseload and peak load demand. The RUPTL indicates that baseload power plants under this category could cover hybrid renewable and gas power plants whose generation costs are lower than that of coal projects.

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Figure 3. Shares of Additional Power Capacity Addition per RUPTL 2021-2030 (OECD, 2021)

Despite the commitment to achieve 23% renewables share in the energy mix by 2025, RUPTL 2021–2030 still shows high reliance on fossil fuels for the next decade, particularly coal. As of January 2023, there are 88 CFPPs operating across the country totaling 40.6 GW of installed capacity. An additional 18.9 GW of capacity is under construction, 4.7 GW in the pre-permit and permit phase, and 2.8 GW announced (GEM, 2022). In the past two decades, Indonesia has maintained steady additions of capacity to keep up with projected demand growth. These additions were made possible through a series of fast-tracked capacity expansion programs for CFPPs, with the aim of adding 42.5 GW capacity by 2024 (Antara News, 2019).

The realised demand growth has been consistently overestimated, resulting in excess capacities. Two of the largest grids in the country, Java-Bali and Sumatra, are expected to have a reserved margin of up to 60% and 56% by 2030, respectively, according to PLN forecasts. In essence, the national grid is facing an oversupply over the next decade (IEEFA, 2021a).

The planning document has indicated that PLN will retire its CFPP fleet, hence aligning with the government commitment in achieving the carbon neutral target in 2060. Starting in 2030, the retirement will be done in stages and in accordance with Power Purchase Agreements (PPA) and economic life-cycle considerations. The plan proposes the first phase of CFPP retirement of 1.1 GW of subcritical units that have adequately reached the end of their designed lifetimes. The units located in Muara Karang, Tanjung Priok, Tambak Lorok, dan Gresik have been operating for 50–60 years, and are considered to be retired in 2030 in RUPTL 2021-2030 (MEMR, 2021). However, PLN may decide to prolong the operational lifetime of its plants by up to 20 years through refurbishment, retrofit or life extension for certain CFPPs that are still considered assets, as cited in RUPTL 2021-23 (MEMR, 2021, p. V-66). This would disrupt efforts to reach emission reduction targets.

National efforts and international support

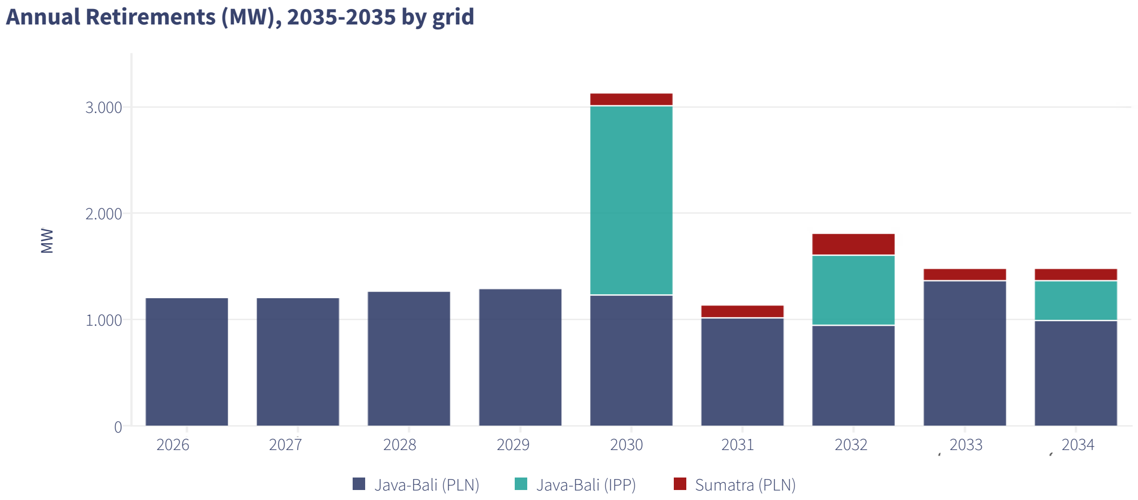
Based on the historical electricity consumption trend, it is clear that the country should reduce or delay capacity expansion and pursue early retirement of the less efficient, older CFPPs, while load growth resumes. The Ministry of Energy and Mineral Resources started to work with PLN to develop a staged retirement plan, designed to meet Indonesia's Net Zero Emissions 2060 roadmap. As the preliminary initial plan, PLN announced the targets to retire 1 GW of CFPPs before 2030 and implement phased retirements up to 2055 when the last unabated CFPP is expected to be retired (Fiscal Policy Agency, 2022).

In October 2022, Presidential Regulation No. 112 Year 2022 on the Acceleration of Renewable Energy Development for the Provision of Electricity was issued. The regulation showcases the country's commitment to prioritising new and renewable power plants and transitioning away from fossil fuels. The regulation details that Indonesia will not allow additional CFPPs to be built after its issuance and set 2050 as the maximum limit of the operational year. New CFPPs are only permitted for those that have been included in RUPTL and Indonesia's National Strategic Project due to the expected contribution to job creation and economic growth.

The regulation also includes that exceptions may apply to coal power plant operations that are able to fulfil the commitment to reduce greenhouse gas emissions by at least 35% within 10 years since the start of operation, through technology implementation, carbon offsets, and/or renewables energy mix. The emissions baseline would be the average emission of PLTU in Indonesia in 2021 (MEMR, 2022a).

The Government of Indonesia and the Asian Development Bank (ADB) officially introduced the Energy Transition Mechanism (ETM) Country Platform to pursue the country's 2060 Net Zero Emissions target (MEMR, 2022b) at the G20 Summit in November 2022. To achieve this and to reduce Indonesia's carbon emissions by 32% by 2030, the country aims to speed up the retirement of 33 coal power plants which amount to a total capacity of 16.8 GW.

The ETM Country Platform targets acceleration of renewables and low-emissions technology development, and ultimately deploying 700 GW of renewable energy plants. The total required investment amount will be up to USD 1 trillion (IDR 15 quadrillion) by 2060 with the support of international partners such as ADB, Islamic Development Bank, and World Bank (ADB, 2022; MEMR, 2022b). The initial retirement plan has been developed by Indonesia under the ADB ETM initiative, listing priority power plants that are best suited for retirement before and after 2030. The annual capacities listed in this initial plan are illustrated in Figure 4 below.


Annual Retirements (MW), 2035-2035 by grid

Source: GEM. (2022). Global Coal Plant Tracker. Indonesia.

Figure 4. Annual future retirement plan of the coal plants for Java Bali (PLN), Java Bali (IPP), and Sumatra (PLN) developed under the ADB ETM initiative (GEM, 2022; Fiscal Policy Agency, 2022).

At the same G20 Summit event, the United States, European Union, Canada, Japan, and the UK announced the Just Energy Transition Partnership (JETP) with Indonesia to financially support the country in its climate targets and energy transition, and to keep in line with the 1.5 degrees target. The targets will be achieved through USD 20 billion in public and private funding over three to five years (European Commission, 2022a).

The partnership is meant to help Indonesia reach Net Zero Emissions by 2060 or sooner by accelerating the decarbonization of Indonesia's power sector. This includes early retirement of some coal plants, while increasing the share of renewables. The agreement requires the country to cap its power sector emissions at 290 million tons (CO2) in 2030, down from the baseline value for 2030 of 357 million tons (CO2) (European Commission, 2022b). The share of renewable energy in the electricity sector is to be increased from 23% to 34% by 2030.

The agreement also includes the target of achieving net zero emissions in the power sector by 2050. In addition, the early retirement of coal-fired power plants will be prioritised as well as halting the pipeline of planned on-grid CFPPs included in the RUPTL (Ember, 2023).

Another form of international support for Indonesia's energy transition is the Climate Investment Funds (CIF) program Accelerating Coal Transition (ACT), an initiative to aid coal-dependent countries reduce their dependence on coal power and be on track to meet global commitments made in the 2016 Paris Agreement commitment (CIF, 2023). The ACT plan developed together with the ADB and World Bank, comprises three key elements: Accelerated CFPP Retirement; Governance, Just Transition and Repurposing; and Scale Up of Renewable Energy and Storage.

Pollution control and emission regulation

The air pollutants of greatest concern emitted by coal-fired power plants are fine particulate matter of $PM_{2.5}$, sulphur dioxide (SO_2), nitrogen dioxide (NO_x), mercury, and other heavy metals. Due to relatively lax air pollutant emissions standards, the majority of Indonesia's coal-fired power plants lack air pollutant control technologies for SO_2 and NO_x. These pollutants make a significant contribution to $PM_{2.5}$ pollution through the formation and release of sulphate and nitrate aerosols, a form of $PM_{2.5}$, in the atmosphere.

In recent years, numerous new CFPPs have been built to meet the increasing electricity needs of Indonesia (GEM, 2023). The share of CFPPs in total power generation has increased substantially in the Southeast Asian region, particularly in Indonesia, nearly doubling from about 25% in 1995 to 52% in 2014, reaching 67% in 2022 (MEMR, 2023b). Indonesia also has the highest share of coal-fired power in its generation mix among ASEAN countries (ERIA, 2017).

As highlighted by the Economic Research Institute for ASEAN and East Asia (ERIA), coal can be considered one of the cheapest fuel sources for power generation in terms of direct cost but comes at a significant cost of public health. While raising emissions standards generally leads to an electricity tariff increase, this would be the most desirable and sustainable outcome for the country to allow proper installation and continued operation of Air Pollution Control (APC) equipment in all operational CFPPs.

Once emission standards are implemented, the country has the responsibility to ensure proper management of APC and provide disclosure of monitoring records. Open access to these records serves as evidence for regulatory compliance, while simultaneously gaining public support, especially for those living close to CFPPs. ERIA highlights that the monitoring system should be highly transparent, monitoring levels at the plant level and the local regions.

Indonesia has implemented two key regulations on controlling emissions from CFPPs: the Ministerial Decree of the Ministry of Environment and Forestry No 21. Year 2008 on Static Emission Sources Quality Standard for Business and/or Activities of a Thermal Power Plant, and the Ministerial Decree of the Ministry of Environment and Forestry No. P.15/MENLHK/SETJEN/KUM.1/4/2019 on Emissions Quality Standard of Thermal Power Plant (Ministry of Environment and Forestry, 2023).

The latter introduced standards for “new” coal power plants that are better aligned with standards enforced in other major coal-consuming countries. However, already permitted and under-construction power plants are not considered “new” by the government when enforcing the standards, allowing them to follow the lax standards for “existing” power plants. CFPPs with a capacity of 25 MW and higher, as well as CFPPs with a capacity of less than 25 MW that operate continuously and use coal with a sulphur content larger than 2%, are mandated to measure their emissions using a Continuous Emission Monitoring System (CEMS). The summary of the maximum levels of pollutants at coal plants is provided in Table 1 below.

Table 1. Summary of Indonesia’s CFPP maximum emission limits

Regulation	Operation year	SO_2 (mg/Nm^3)	NO_x (NO_2) (mg/Nm^3)	PM (mg/Nm^3)	Opacity	Mercury (mg/Nm^3)
Permen LHK No 21 Tahun 2008 **(prior)**	Before 01 Dec. 2008	750	850	150	20%	
	After 01 Dec. 2008	750	750	100	20%	
Permen LHK No. P.15/MENLHK/ SETJEN/ KUM.1/4/2019 **(in-force)**	Before 23 April 2019	550	550	100		0.03
	After 23 April 2019	200	200	50		0.03

A three-year project, “Transparent Pollution Control in Indonesia” that runs from March 2021 until February 2024, aims to support Indonesia in reaching international goals of energy transition. Indonesia receives financial support from the EU to improve industrial pollution monitoring, through the implementation of the Pollutant Release and Transfer Register (PRTR). The project also aims to establish a stronger civil advocacy network in Indonesia, to engage with the national stakeholders and push for an immediate response (EEAS, 2021; Simon, 2023).

Nexus3 Foundation highlights the urgent need to control air pollution, citing the 2019 Citizen Lawsuit submitted by 32 citizens which is addressed to President Joko Widodo, the Minister of Environment and Forestry, Minister of Health, and Minister of Internal Affairs, as well as the Governor of West Java and the Governor of Banten. Air pollution in Jakarta is mainly associated with six coal-fired power plants located in the nearby three provinces, emissions from millions of vehicles, and industrial activities. High levels of pollution have been a result of unenforced emissions testing and a lack of national and subnational efforts to reduce pollutant release (Nexus3 Foundation, 2021).

Methodology

This study quantifies the health impacts of air pollutant emissions from coal power generation in Indonesia using the impact pathway approach. This approach is the most common way to study the health impacts of air pollutant sources, following the chain of causation from emissions, to atmospheric dispersion and chemical transformation, population exposure, resulting health impacts, and the economic cost of those health impacts. The impacts are quantified for a range of future pathways, from the pathway implied by the current regulations, as well as a pathway that is aligned with 1.5 degrees target for utility power plants and a pathway that is aligned with 1.5 degrees target for both captive and utility power plants. The study also quantifies the long-term impacts of mandating more stringent air pollutant emission controls and different levels of biomass co-firing.

The analysis carried out in this work is done by:

(1) Developing a plant-by-plant inventory of emissions;
(2) Estimating pollution dispersion from CFPPs through atmospheric modelling;
(3) Quantifying air pollution health impacts resulting from changes in ambient concentration; and
(4) Valuing health impacts in monetary terms using a cost of illness method.

The analysis was carried out in a spatial grid with a 5x5 km resolution, with health impacts calculated for each grid cell. All datasets were aggregated or interpolated to this resolution as required.

Emissions inventory

CREA compiled a plant-level emissions inventory of all operational CFPPs in Indonesia, to be used as inputs to air quality modelling. The inventory includes plant-specific information on combustion and generation technologies, power generation capacity and plant location, pollutant flue gas concentrations. It also includes stack information, namely stack height and diameter, flue gas release velocity, and temperature. The stack characteristics are used to model plume release height and the thermal rise of pollutants.

The first compilation on existing, under construction, and planned coal power plants were taken from the Global Energy Monitor (GEM) Global Coal Plant Tracker (GCPT) (GEM, 2023). Basic information includes plant coordinates, generating capacity, start year of operation, and status (operating, under construction, permitted, pre-permit, announced). The initial inventory is then cross-verified and complemented with information compiled from local partners. Further data compilation was conducted to obtain available data on plant-specific emissions data from official reports, voluntary operator reports, Environmental Impact Assessment (EIA) documents, national emissions standards and other relevant regulations..

Since the emission volumes of coal-fired power plants are not disclosed publicly in Indonesia, emissions mass rate (E) of the main air pollutants (SO_2, NO_x, PM) were calculated using the formula:

$$E = \frac{CAP \times CF}{EFF} \times SFGV \times FGC$$

where CAP is the gross electric generation capacity of the plant unit (MW), EFF is the thermal efficiency (gross, on Lower Heating Value (LHV) basis, in MJ/kg), CF is the capacity factor, SFGV is the specific flue gas volume of the coal (Nm^3/GJ) and FGC is the flue gas concentration of the pollutant (mg/Nm^3).

Mercury emissions were calculated as:

$$E = \frac{CAP \times CF}{EFF} \times \frac{1}{CAL} \times C_{Hg} \times (1 - C)$$

Where CAL is the calorific value of the coal, C_{Hg} is the mercury content in coal and CE is the mercury control efficiency.

- Information on FGC was collected from a wide range of sources including the plant operator's website, their CSR and financial reports as well as data from environmental impact assessments. We also sourced academic studies that had plant-specific data. The information was then generalised to other power plants, creating separate categories for small plants (<100MW), new plants (commissioned since 2015), and for SO_2 and NO_x, plants equipped with emission control devices for these pollutants.

- When plant thermal efficiency was not available, gross efficiency of 44% on an LHV basis was assumed for ultra-supercritical plants, 42% for supercritical plants, 38% for subcritical plants built since 2010, and 35% for plants built earlier. These are assumptions generalised from available data for plants of different types. For small units with less than 100 MW capacity, 30% was assumed.

- Specific flue gas volume of 379 Nm^3/GJ (corrected at 7% oxygen) was used, calculated as the average of Indonesian coal samples in the USGS World Coal Quality Inventory (USGS, 2019).

- Coal power capacity and generation in the current policies and 1.5 degrees scenarios were taken from the GCAM simulations (Cui et al., 2022). Captive power plants were assumed to operate at 80% utilisation, while utility power plants followed the utilisation projected by GCAM.

- Mercury content in coal used as fuel sources in 47 CFPPs in Indonesia was obtained from a survey on national mercury emissions from CFPPs in Indonesia (BCRC-SEA, 2017). Mercury control efficiency was based on values specific to coal type and air pollutant control technology in UNEP (2017) Mercury Toolkit.

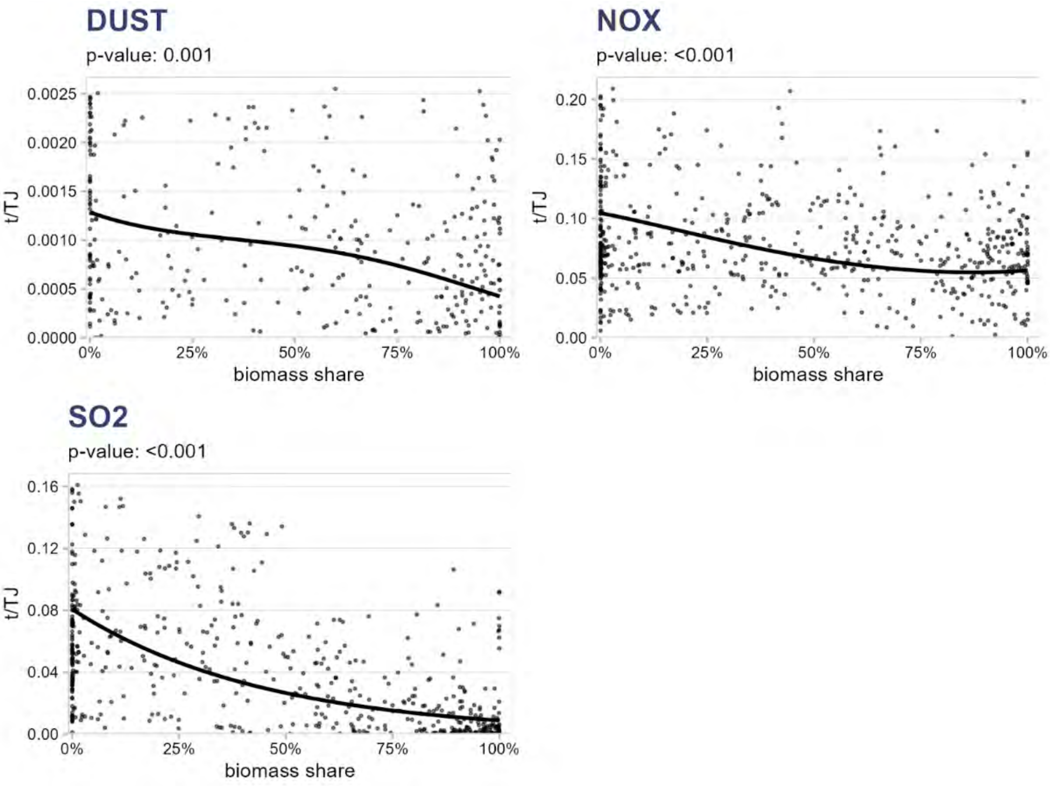
- The effect of biomass co-firing on emissions was projected using relationships derived from EU emissions data (EEA, 2023). This data contains annual fuel input and air pollutant emissions for hundreds of large combustion plants, allowing us to quantify the effect of variations in the shares of biomass and coal year-to-year at the same facility (Figure 5).

- We assumed the application of CCS reduces SO_2, NO_x, and PM emissions by 85%, 29%, and 6%, respectively, based on research by the European Environment Agency (EEA, 2011).

Where information on a plant's emissions values was lacking or unavailable, it was generalised using average values for projects with similar capacity and combustion technology. We assumed that such plants were in compliance with the country's emissions standards and fully operating their emission control devices. Information on installed emission controls was also collected from these primary documents, as well as the S&P (2020) World Electric Power Plants database.

To assess the life-cycle emissions of plants that are currently under construction and without a known date of operation, these plants are assumed to come online in 2025. As for projects that are not yet under construction and without a known operating date, the power plants are assumed to come online by 2028. For delayed projects, i.e. under construction plants that had a targeted operating date in the past, the operating date was assumed to be 2023. Similarly, for new projects not yet under construction, it was assumed that projects currently permitted would come online in 2026 at the earliest, projects in the "pre-permit" stage in 2027, and "announced" projects in 2028.

In the Air Pollution Control (APC) scenarios, retrofitted plants were assumed to meet the more lenient end of the EU Best Available Technology reference levels: 130 mg/Nm^3 for SO_2, 150 mg/Nm^3 for NO_x and 10 mg/Nm^3 for PM[1] (European Commission, 2021). For mercury, mercury-specific controls with 75% control efficiency were assumed, based on UNEP's (2017) Mercury Toolkit.



Source: Centre for Research on Energy and Clean Air (CREA) analysis based on European Environment Agency (EEA) data.

Figure 5. Effect of biomass co-firing on emissions of major air pollutants, derived from European Union Industrial Reporting Database (EEA, 2023)

Atmospheric modelling

CREA simulated air pollutant concentrations using the CALPUFF air dispersion model, version 7 (Exponent, 2015). CALPUFF is a widely-used industry standard model for long-range air quality impacts of point sources. The model has been evaluated extensively by the US Environmental Protection Agency, is open-source, and fully documented. CALPUFF calculates the atmospheric transport, dispersion, chemical transformation, deposition of the pollutants, and the resulting incremental ground-level concentrations attributed to the studied emissions sources. Chemical transformations of NO to NO_2 as well as SO_2 and NO_2 to $PM_{2.5}$ are calculated using the ISORROPIA chemistry module in CALPUFF.

Background concentrations of oxidants (ozone, ammonia, hydrogen peroxide) are taken from simulations using the Geos-Chem global atmospheric model with a nested grid for Southeast Asia (Koplitz et al., 2017). Meteorological input data for the year 2021 are generated from the Weather Research Forecasting (WRF) model (Skamarock et al., 2008), version 4.2.2. WRF was set up with 33 vertical levels and two nested grids. These are shown in Figure 6.

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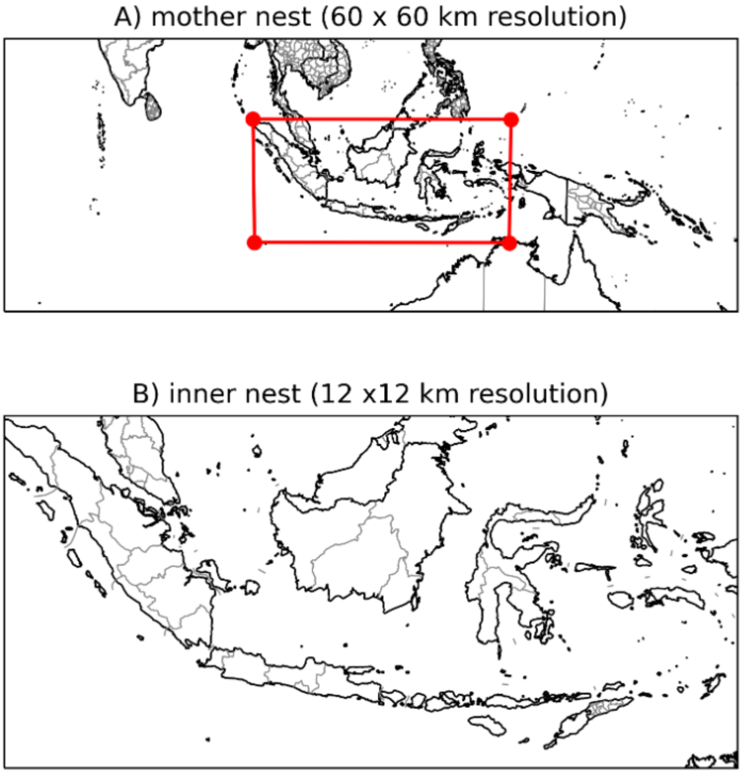
[1] The levels for SO_2 and NO_x are obtained from the yearly average higher end of 300 MW and larger coal-fired PC boilers for existing plants; and the level for PM is the yearly average higher end of 300-1,000 MW for existing plants.


A) mother nest (60 x 60 km resolution)

B) inner nest (12 x12 km resolution)

Source: Centre for Research on Energy and Clean Air (CREA).

Figure 6. Maps of mother and inner nests in WRF meteorological model

The mother nest has a grid resolution of 60 km and spans approximately 12,000 km in the east-west direction and 4,600 km in the north-south direction. The inner nest has a grid resolution of 12 km, spanning roughly 4,000 km in the east-west and 2,000 km in the north-south direction. Land-use data were obtained from the European Space Agency (2018), and terrain elevation data were obtained from NASA Shuttle Radar Topography Mission (SRTM) high-resolution datasets (Farr et al., 2007).

Mother and inner domains use a two-way nesting technique which ensures dynamic interaction between them. WRF simulations use initial and lateral boundary conditions from the National Centers for Environmental Prediction's (NCEP) Climate Forecast System Reanalysis (CFSR) dataset (Saha et al., 2014) of the National Oceanic and Atmospheric Administration (NOAA), producing three-dimensional, hourly meteorological data covering the full calendar year of 2021. For assessment of annual average pollutant concentrations, emissions are assumed to be constant throughout the year.

The power plant units were modelled as buoyant point sources, taking into account the stack height and thermal plume rise from the stacks. This requires input data on the stack characteristics: stack height, stack inner diameter, flue gas exit velocity, and temperature. Information on these characteristics was collected manually from a wide range of public sources for as many power plants as possible and generalised to the other plants by building a linear regression model predicting each of the stack characteristics based on the properties of the plant. The predictors used in the model were plant capacity, commissioning year, and in the case of flue gas temperature, the presence of an SO_2 scrubber, which lowers the temperature.

The power plants were grouped into clusters, with units within 1 km of each other and with similar stack characteristics grouped together as one point source, to make the computing requirements manageable. This resulted in a total of 145 modelled clusters, as illustrated in Figure 2. Separate model simulations were performed for each cluster.

Health and economic impacts assessment

We used CREA's detailed and globally implementable health impact assessment framework based on the latest science to estimate the impacts of air pollution on public health. This framework includes as complete a set of health outcomes as possible without obvious overlaps. The emphasis is on outcomes for which incidence data are available at the national level from global datasets and outcomes that have high relevance for healthcare costs and labour productivity. These health endpoints were selected and quantified in a way that enables economic valuation, adjusted by levels of economic output and income in different jurisdictions.

For each evaluated health outcome, we have selected a concentration-response relationship that has already been used to quantify the health burden of air pollution at the global level in peer-reviewed literature. This indicates the evidence is mature enough to be applied across geographies and exposure levels. The calculation of health impacts follows a standard epidemiological calculation:

$$\Delta cases = Pop \times \sum_{age} \left[Frac_{age} \times Incidence_{age} \times \frac{RR_{conc,age} - 1}{RR_{conc,age}} \right],$$

where **Pop** is the total population in the grid location, age is the analysed age group (in the case of age-dependent concentration-response functions, a 5-year age segment; in other cases, the total age range to which the function is applicable), **Frac**$_{age}$ is the fraction of the population belonging to the analysed age group, **Incidence**$_{age}$ is the baseline incidence of the analysed health condition, and **conc** is the pollutant concentration, with **conc**$_{base}$ referring to the baseline concentration (current ambient concentration). RR$_{(conc,age)}$ 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 function becomes:

$$RR(c) = [RR_0 \times c] - [c_0 \times \Delta c_0], \text{ ketika } c > c_0$$

$RR(c) = 1$ otherwise, where RR_0 is the risk ratio found in epidemiological research, Δc_0 is the concentration change that RR_0, and c_0 is the assumed no-harm concentration (in general, the lowest concentration found in study data).

Data on total population and population age structure were taken from Global Burden of Disease results for 2019 (Global Burden of Disease, 2020), distributed by the Institute for Health Metrics and Evaluation (IHME) (IHME, 2020). The spatial distribution of population within each city and country, as projected for 2020, was based on the Gridded Population of the World v4 from the Center for International Earth Science Information Network (CIESIN, 2018). Following the update of the WHO Air Quality Guidelines (WHO, 2021), which now recognizes health harm from NO_2 at low concentrations, we use the mortality risk function for NO_2 based on the findings of Huangfu and Atkinson (2020), and include impacts down to 4.5 µg/m^3, the lowest concentration level in studies that found increased mortality risk, tabulated in Table 2.

Adult deaths were estimated using the risk functions developed by Burnett et al. (2018), as applied by Lelieveld et al. (2019). Deaths of children under the age of five from lower respiratory infections linked to $PM_{2.5}$ pollution were assessed using the Global Burden of Disease risk function for lower respiratory diseases (IHME, 2020). For all mortality results, cause-specific data were taken from the 2019 Global Burden of Disease project results (IHME, 2020).

Health impact modelling projects the effects of pollutant exposure during the study year. Some health impacts are immediate, such as exacerbation of asthma symptoms and lost working days, whereas other chronic impacts may have a latency of several years. Concentration-response relationships for emergency room visits for asthma and work absences were based on studies that evaluated daily variations in pollutant concentrations and health outcomes. These relationships were applied to changes in annual average concentrations. The annual average baseline concentrations of $PM_{2.5}$ and NO_2 were taken from van Donkelaar et al. (2021) and Larkin et al. (2017), respectively. Since the no-harm concentration for SO_2 is very low and the risk function is linear with respect to the background concentration, there was no need for data on SO_2 background concentrations.

To understand the health impacts in the future, the study took into account the projected changes in population, population age structure, and mortality by age group, based on the UNDP (2019) World Population Prospects Medium Variant. This factors in the expected reduction in baseline infant mortality and increase in premature deaths from chronic diseases in older adults as a part of the population and epidemiological transitions and improvements in health care. In 2022, CREA provided the Institute for Essential Services Reform and the University of Maryland health impact assessments, which estimated 8,700 deaths caused by emissions from coal-fired power plants every year. This report incorporates far more detailed air pollutant dispersion modelling and refined emissions inventories and takes into account the health impacts of exposure to SO_2 and NO_2, in addition to $PM_{2.5}$.

Table 2. Input parameters and data used in estimating physical health impacts

Age group	Effect	Pollutant	Concentration response function	Concentration change	No-risk threshold	Reference	Incidence data
1–18	New asthma cases	NO_2	1.26 (1.10 – 1.37)	10 ppb	2 ppb	Khreis et al. (2017)	Achakulwisut et al. (2019)
0–17	Asthma emergency room visits	$PM_{2.5}$	1.025 (1.013 – 1.037)	10 µg/m^3	6 µg/m^3	Zheng et al. (2015)	Anenberg et al. (2018)
18–99	Asthma emergency room visits	$PM_{2.5}$	1.023 (1.015 – 1.031)	10 µg/m^3	6 µg/m^3	Zheng et al. (2015)	Anenberg et al. (2018)
Newborn	Preterm birth	$PM_{2.5}$	1,15 (1.07 – 1.16)	10 µg/m^3	8.8 µg/m^3	Sapkota et al. (2012)	Chawan Paiboon et al. (2018)
20–65	Work absence	$PM_{2.5}$	1.046 (1.039 – 1.053)	10 µg/m^3	N/A	WHO (2013)	EEA (2014)
0–4	Deaths from lower respiratory infections	$PM_{2.5}$	IHME (2020)		5.8 µg/m^3	IHME (2020)	IHME (2020)
25–99	Deaths from noncommunicable diseases, disaggregated by cause, and from lower respiratory infections	$PM_{2.5}$	Burnett et al. (2018)		2.4 µg/m^3	Burnett et al. (2018)	IHME (2020)

25–99	Disability caused by diabetes, stroke and chronic respiratory disease	$PM_{2.5}$	IHME (2020)		2.4 µg/m^3	Burnett et al. (2018)	IHME (2020)
25–99	Premature deaths	NO_2	1.02 (1.01 – 1.04)	10 µg/m^3	4.5 µg/m^3	Huangfu & Atkinson (2020); NRT dari Stieb et al. (2021)	IHME (2020)
25–99	Premature deaths	SO_2	1.02 (1.01–1.03)	5 ppb	0.02 ppb	Krewski et al. (2009)	IHME (2020)

Note: Numeric values in the column "Concentration-response function" refer to odds ratio corresponding to the increase in concentrations given in the column "concentration change." Literature references indicate the use of a non-linear concentration-response function. No-harm threshold refers to a concentration below which the health impact is not quantified, generally because the studies on which the function is based did not include people with lower exposure levels. Data on concentration-response relationships do not exist for all geographies, so a global risk model is applied to all cities. Incidence data are generally unavailable at the city level so national averages have to be applied.

Air pollution increases the risk of developing respiratory and cardiovascular diseases and complications related to them, significantly lowering the quality of life and economic productivity of people affected while increasing healthcare costs. Economic losses as a result of air pollution were calculated using the methods outlined in Myllyvirta (2020). The valuation of deaths was updated to the values derived by Viscusi and Masterman (2017) which are based on labour market data, and pay particular attention to applicability in middle- and low-income countries.

The Global Burden of Disease project has quantified the degree of disability caused by each disease into a "disability weight" that can be used to compare the costs of different illnesses. The economic cost of disability and reduced quality of life caused by these diseases and disabilities are assessed based on disability weights, combined with the economic valuation of disability used by the UK environmental regulator Department for Environment Food and Rural Affairs (Birchby et al., 2019), and adjusted by GNI PPP for Indonesia. The deaths of young children are valued at twice the valuation of adult deaths, following OECD's recommendations (2012).

The valuation of future health impacts is based on the premise that the long-term social discount rate is equal to the long-term GDP growth rate, and the economic loss associated with different health impacts is proportional to the GDP, resulting in a constant present value of health impacts over time.

Table 3. Input parameters and data used to estimate economic costs of health impacts

Outcome	Valuation at world average GDP/GNI per capita (2017 int. USD)	Valuation in Indonesia		Reference
		(current USD)	(current USD)	
Work absence (sick leave days)	85	22	335,300	EEA (2014)
Number of children suffering from asthma due to pollution exposure (increased prevalence)	1,077	274	4,228,000	Brandt et al. (2012)
Deaths	2,637,000	663,900	10,260,000,000	Viscusi & Masterman (2017)
Deaths of children under 5	5,273,000	1,328,000	20,510,000,000	OECD (2012)
Asthma emergency room visits	232	59	911,800	Brandt et al. (2012)
Preterm births	107,700	27,370	422,800,000	Trasande et al. (2016)
Years lived with disability	28,480	7,171	110,800,000	Birchby et al. (2019)

Cost of air pollution controls

Installation and operating costs for air pollution controls (APC) were compiled from a range of sources, shown in Table A4 in the Appendix. We transferred these costs to Indonesian cost levels by first converting the reported costs to current prices in U.S. dollars, and then using the cross-country estimates of the relative costs of flue gas desulfurization (FGD) and selective catalytic reduction (SCR) (Ferrari et al., 2019) to calculate the average transferred costs, shown in Table A4 in the Appendix. Since Ferrari et al. did not estimate dust control costs, we used the sum of FGD and SCR costs as an indicator of the relative costs of dust controls, as the relative costs of the different control systems are likely to be closely correlated.

Table A5 in the Appendix shows the estimated average costs of the different APC technologies in Indonesia. We used this data to project the additional costs from meeting the more stringent emission standards assumed in the APC scenario, compared with the current APC costs plants have to incur already to meet current national standards. This means that existing plants already have particulate matter controls to operate. This study assumes the inclusion of investment in a rebuilt dust control system to meet more stringent standards, without an increase in operating costs. SO_2 and NO_x controls need to be added, with their full capital and operating costs included as an additional cost.

Unlike existing plants, new plants in Indonesia are already mandated to install FGD, and SNCR and dust controls to comply with national emission standards. We assumed that the additional capital and operating costs of a higher-performance FGD and dust control are 50% of the full cost shown in Table A5, a conservative assumption. For NO_x control, we assumed that the plants installed SCR instead of SNCR, and assigned the difference as an additional cost. For future projections, we assumed that the cost escalation of the APC technologies is equal to the long-term average GDP growth rate.

Evaluation of different phase-out timelines

CREA has developed and modelled three distinct scenario pathways based on CFPP retirement schedules applicable to the national electricity provider namely PLN and the IPPs, CFPP retirement schedule applicable to captive power plants, implementation of co-firing in CFPP operation, and installation of Air Pollution Control (APC) technologies. A summary of the scenarios considered in this study is tabulated in Table 4.

Table 4. Scenario matrix of Indonesia's pathways to a Just Energy Transition

Scenario	PLN & IPP Retirement Schedule	Captive Power Retirement Schedule	Biomass Co-firing	Air Pollution Control Retrofit
PERPRES 112/2022 - referred to as current policies in this study	**14 GW of PLN & IPP** power plants are retired by **2035**, while the **remaining** are retired by **2050**	All captive power plants are retired after 30 years of operation	Phased increase of co-firing share, reaching **20% at PLN power plants by 2030**	APCs are installed to **follow the current national emission limits** until end-of-life
1.5 degrees, excluding captive power plants	Retirement schedule aligned with **IESR-UMD optimised pathway**		Co-firing maintained at currently committed levels, i.e. **5% at most PLN power plants**	APCs are installed to **follow the current national emission limits** until end-of-life
1.5 degrees		Retirement schedule aligned with **IESR-UMD optimised pathway**		

It should be noted that the study considers the retirement schedule defined in the Presidential Regulation (*Peraturan Presiden, Perpres*) No. 112 Year 2022 as the baseline scenario. Under **PERPRES 112/2022 scenario**, a total capacity of 14 GW of PLN and IPP coal plants is to be retired by 2035, while the remaining plants retire by 2050. Captive plants are assumed to retire after 30 years of operation. Furthermore, biomass co-firing is increased to a minimum of 20% by 2030 at PLN power plants to contribute towards the 34% renewable energy target by 2030 set in JETP. APC technology is installed and follows current emission limits until the end-of-life for the plants.

The pathway for retiring Indonesia's coal-fired plants in order to meet the global commitment to limit average global temperature rise to 1.5 degrees by 2030 is derived from the report "Financing Indonesia's Coal Phase-out" by IESR and the University of Maryland (Cui et al., 2022). The **1.5 degrees scenarios** developed in this study maximise the health benefits of the coal phase-out. Under this consideration, the plants with the highest health costs per unit of power generated are retired first within each electric grid.

The **1.5 degrees scenario excluding captive power plants** assumes them to be retired after 30 years of operation. With the inclusion of captive power plants, the scenario assumes their retirement to be aligned with IESR-UMD's optimised pathway. This pathway suggests that Indonesia's coal power generation would decrease by 11% in 2030, by over 90% in 2040, and would be completely phased out by 2045. In absolute numbers, 18 plants would retire by the end of the decade, 39 between 2031 and 2040. The remaining 15 of the 72 non-captive coal plants would be operated at low utilisation levels beyond 2040, and retired by 2045.

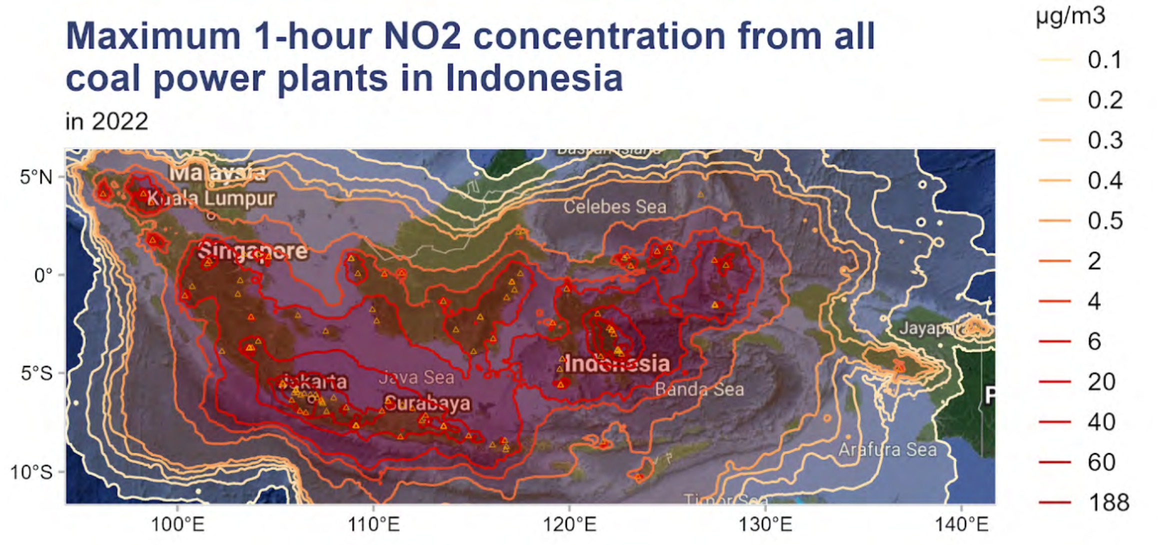
Implications on air pollution

Coal-based power plants emit large amounts of pollutants, namely SO_x, NO_x, and PM, and also heavy metals. This study estimates that all operating coal plants in Indonesia emitted 399 kilotons (kt) of SO_x, 349 kt of NOx, and 73 kt of PM in 2022. Furthermore, an estimated 7,100 kg of mercury was emitted in the same period. Not only do these power plant emissions affect populations in the vicinity of the plants, pollutants are also carried by wind and other atmospheric conditions to farther locations resulting in nation-wide consequences.

Figure 7 shows the maximum 1-hour and 24-hour concentrations of NO_2, SO_2, and $PM_{2.5}$ attributed to coal power in 2022, and it shows high concentration levels of all pollutants throughout Indonesia. We chose between 1-hour and 24-hour maximum plots for each pollutant based on the metric used in the WHO 2005 Air Quality Guidelines which are the basis for Indonesia’s national standards.

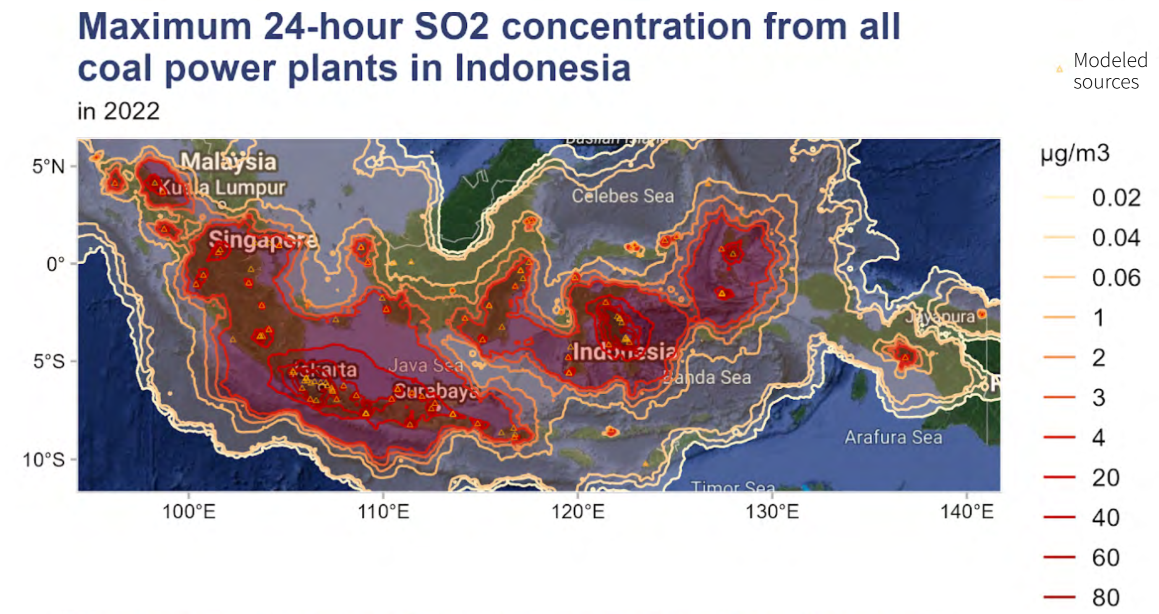
The major hotspots of coal power plant pollution in Indonesia are Banten, Central Sulawesi, Central Java, Riau, Maluku, and North Maluku. Emissions in Banten are dominated by PLN power plants, of which more than half are relatively old (commissioned before 2010). In all the listed provinces outside of Java, captive power plants commissioned after 2010 dominate the emissions. In Central Java, relatively new IPP power plants are the main source.

Figures 8, 9, and 10 visualise the annual mean concentrations of each pollutant type in 2035 by scenario. They are the PERPRES 112/2022 scenario, the 1.5 degrees scenario excluding captive power, and the 1.5 degrees scenario. By 2035, there would be large improvements in air quality by following a coal power retirement pathway that is aligned with the 1.5 degrees target, as shown in the bottom images. Also, for all of the pollutants, there are major changes in air quality between the 1.5 degrees scenario that includes captive power plants retirement and the 1.5 degrees scenario that excludes captive retirement, as shown in the middle and bottom images respectively, especially in Eastern Indonesia where most of the captive power plant fleet is located.



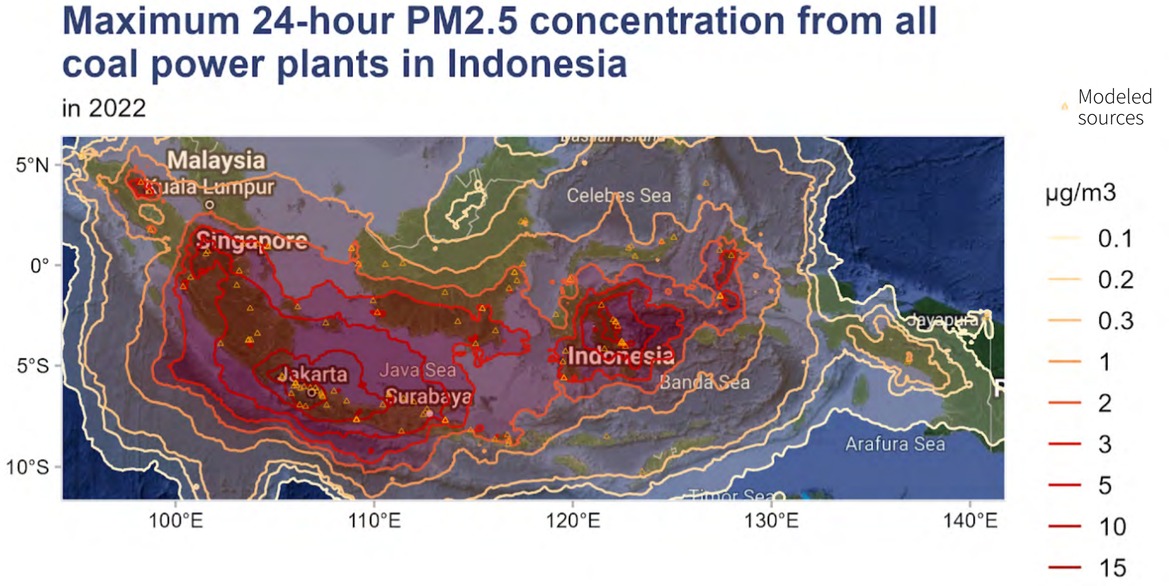
Maximum 1-hour NO2 concentration from all coal power plants in Indonesia

in 2022



Maximum 24-hour SO2 concentration from all coal power plants in Indonesia

in 2022

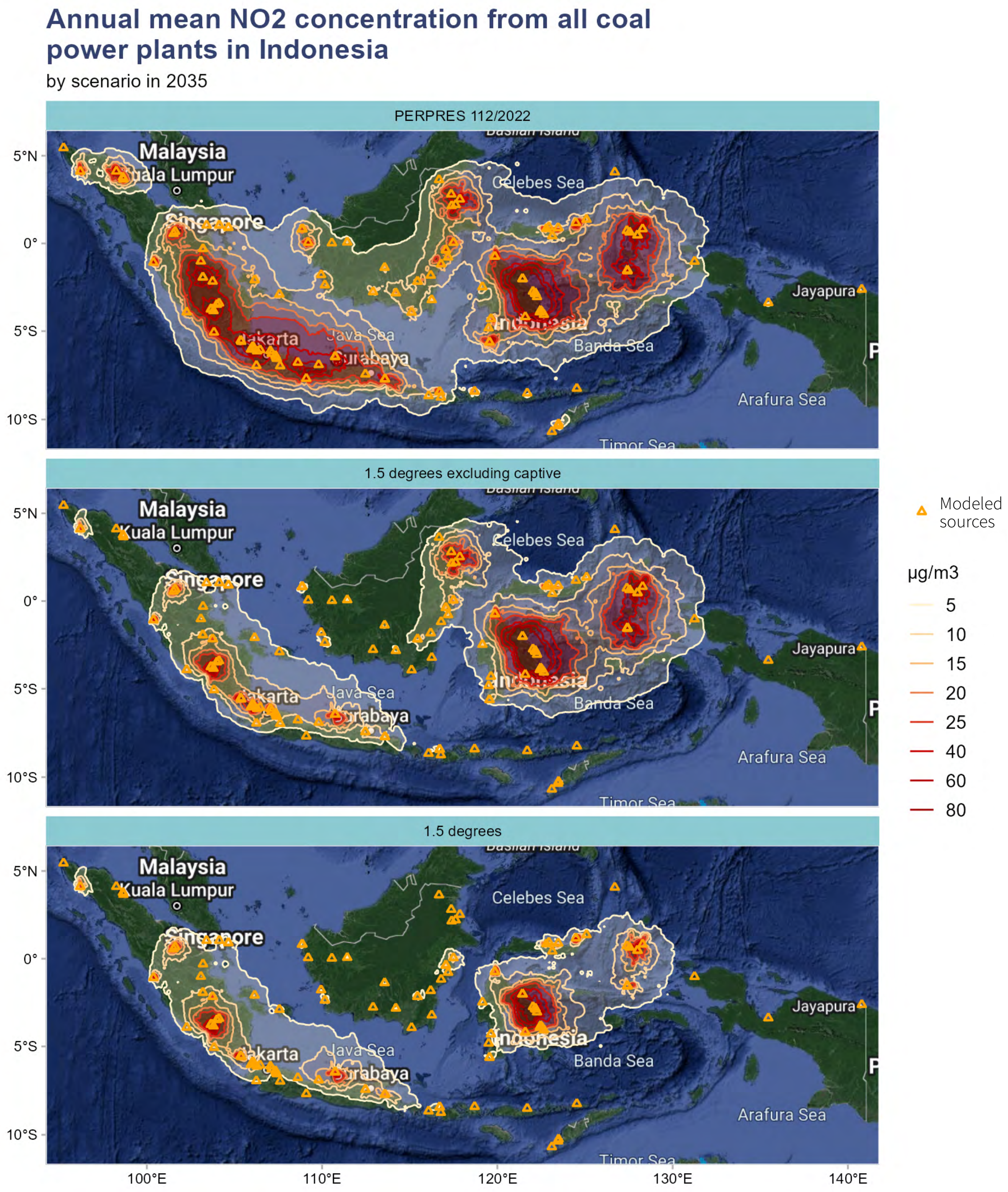


Maximum 24-hour PM2.5 concentration from all coal power plants in Indonesia

in 2022

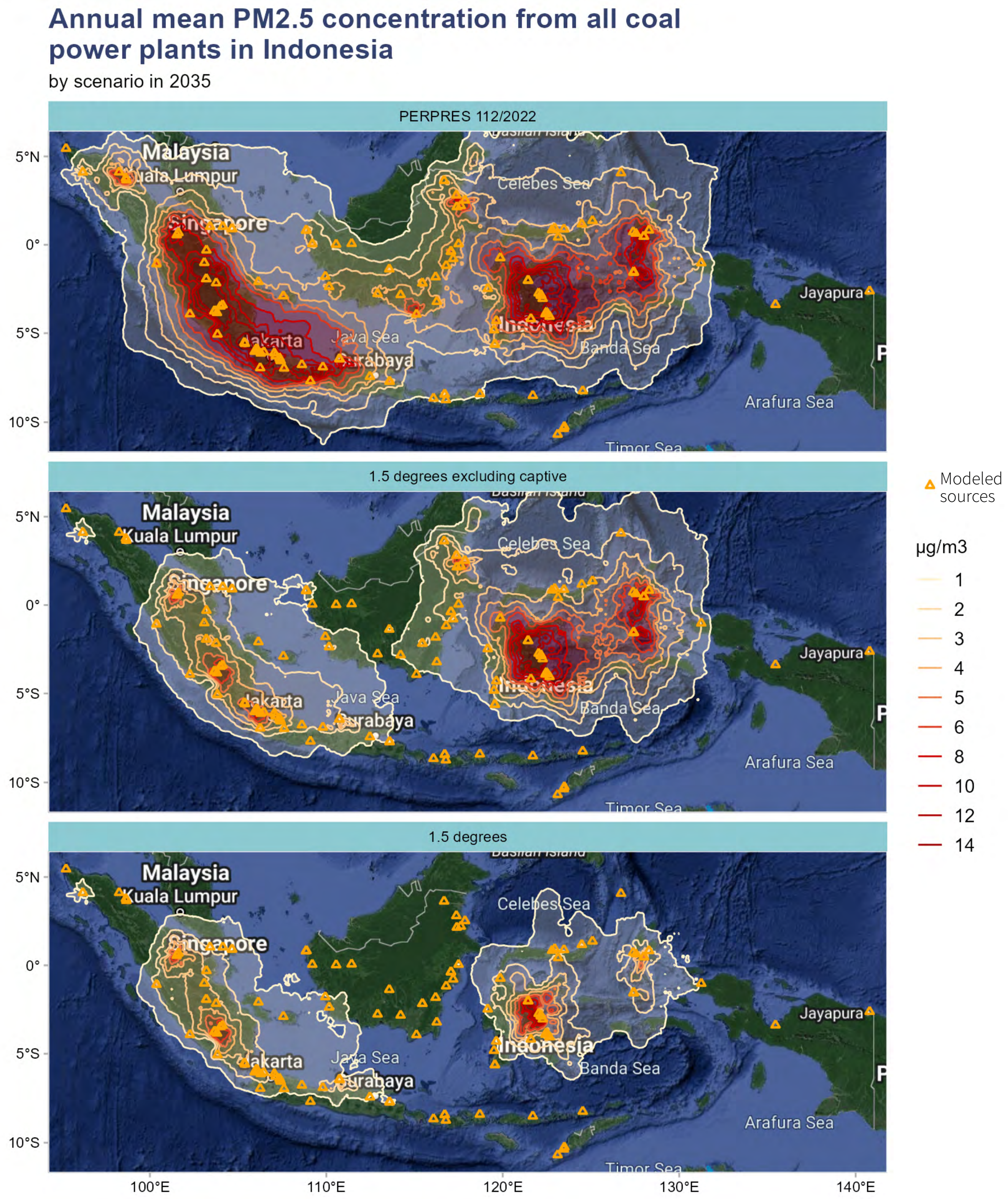
Source: Centre for Research on Energy and Clean Air (CREA).

Figure 7. Maximum 1-hour and 24-hour concentrations from all coal power plants in Indonesia by pollutant in 2022



Source: Centre for Research on Energy and Clean Air (CREA).

Figure 8. Visualised distribution of coal power plants and mean NO_2 concentrations in Indonesia by scenario in 2035

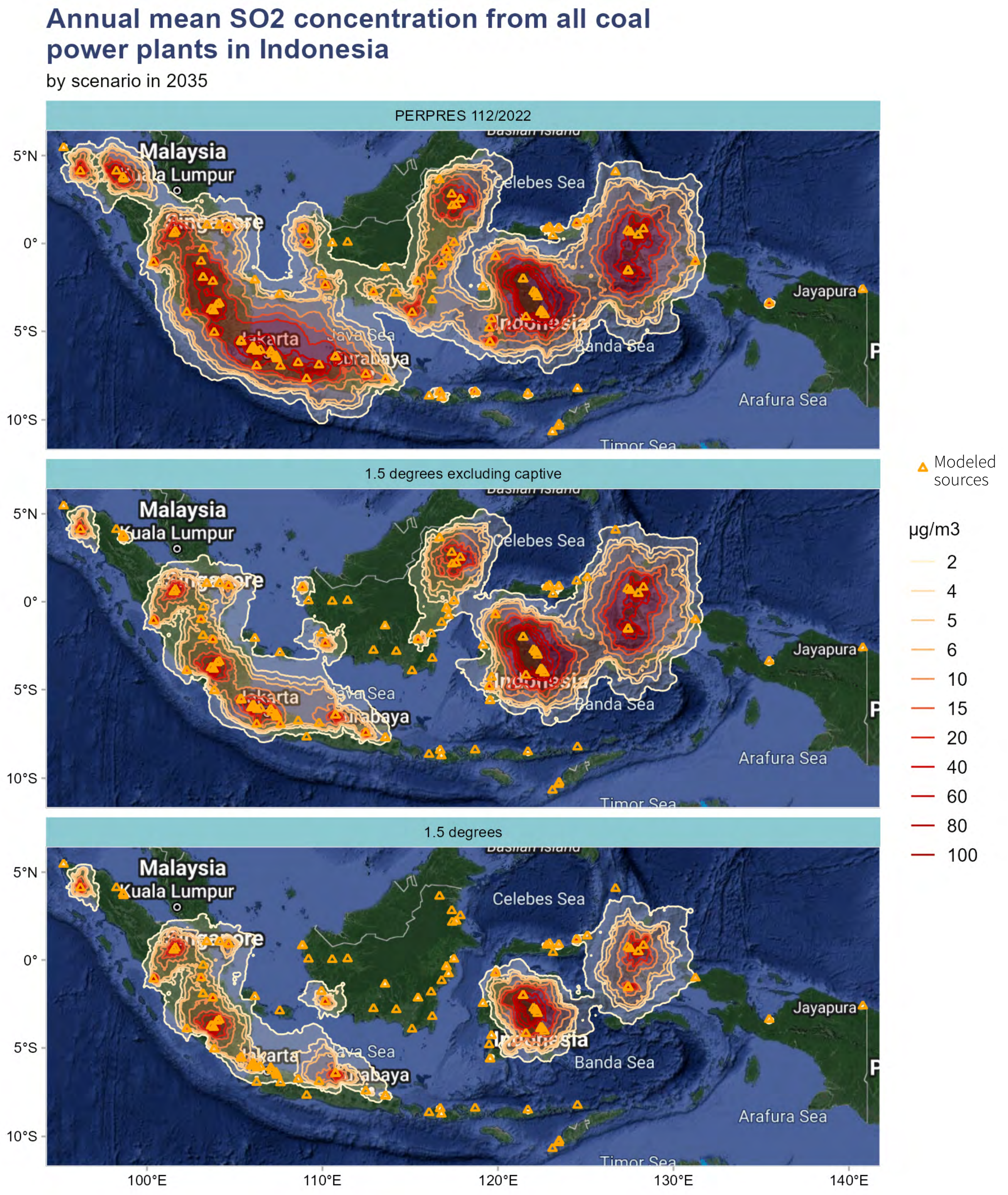


Annual mean PM2.5 concentration from all coal power plants in Indonesia

by scenario in 2035

Source: Centre for Research on Energy and Clean Air (CREA).

Figure 9. Visualised distribution of coal power plants and mean $PM_{2.5}$ concentrations in Indonesia by scenario in 2035


Annual mean SO2 concentration from all coal power plants in Indonesia

by scenario in 2035

PERPRES 112/2022

1.5 degrees excluding captive

1.5 degrees

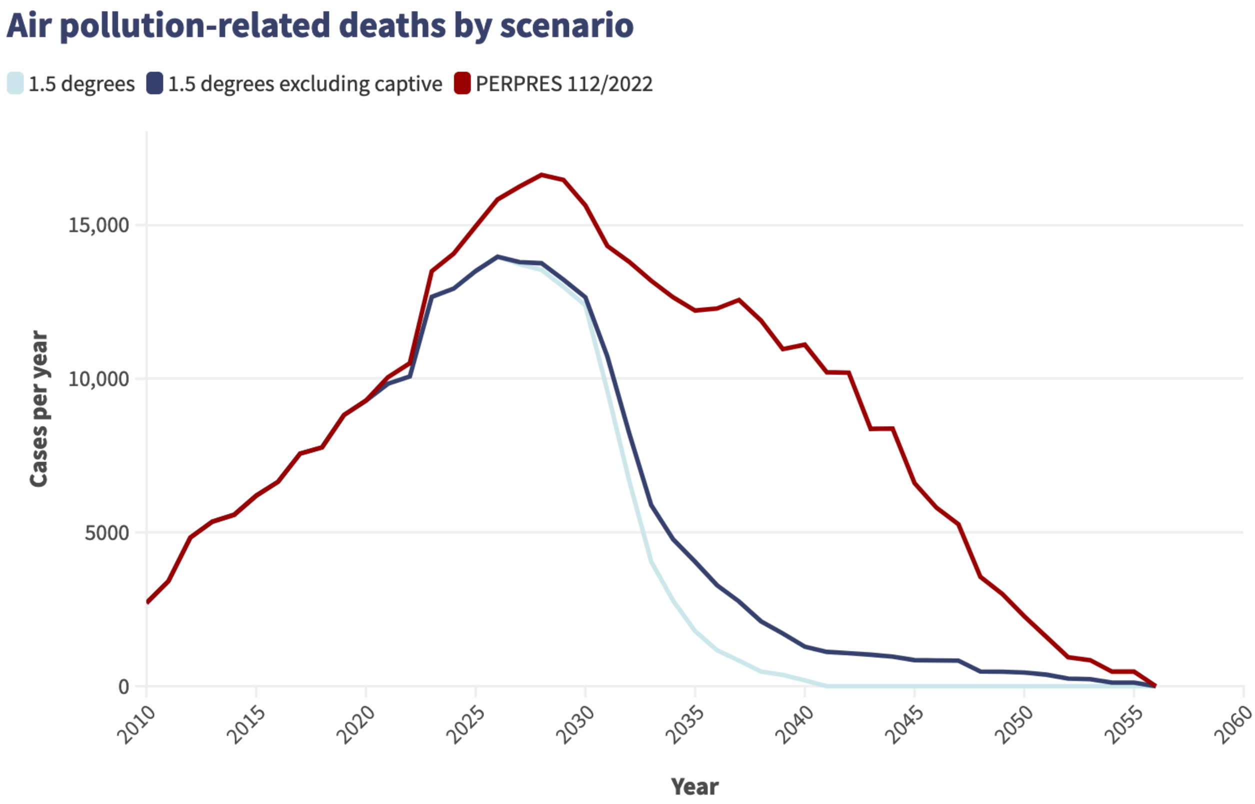
Source: Centre for Research on Energy and Clean Air (CREA).

Figure 10. Visualised distribution of coal power plants and mean SO_2 concentrations in Indonesia by scenario in 2035

Health impacts and cost implications

Annual impacts

Under the current policy measure, PERPRES 112/2022, air pollution from coal-fired power plants was accountable for an estimated 10,500 (95% CI: 6,500–16,400) deaths in 2022 (as illustrated in Figure 11) and health costs amounted to USD 7.4 billion (IDR 109.9 trillion; 95% CI: USD 4.6–11.5 billion, IDR 67.6–170.3 trillion). Air pollution-related deaths are on the rise, and are expected to peak in 2028, with nearly 16,600 deaths annually - nearly a 60% increase in just six years.

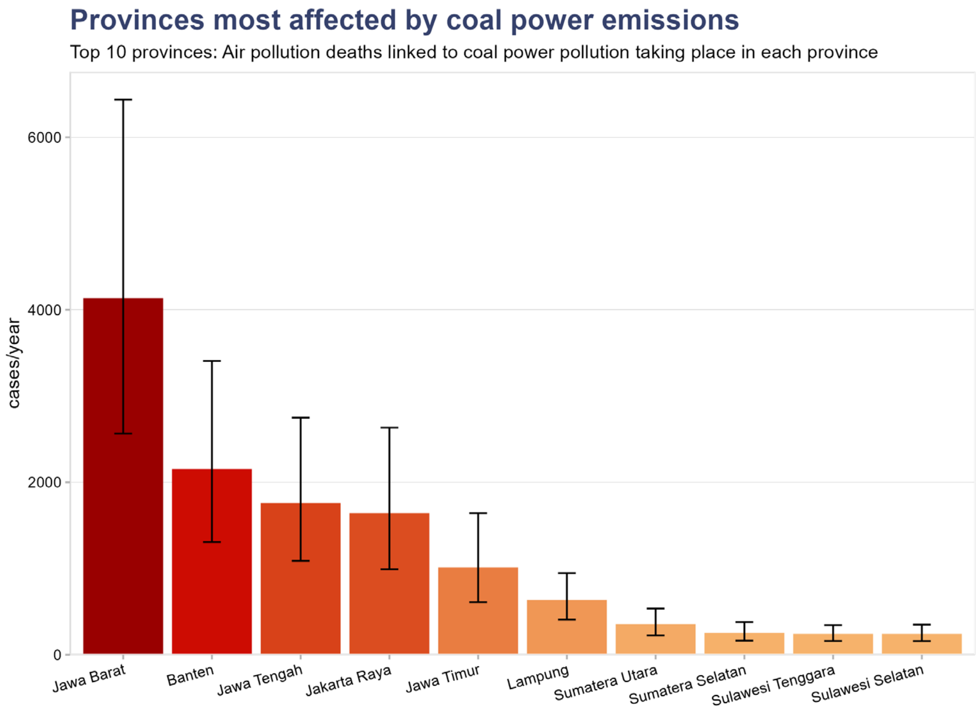


Source: Centre for Research on Energy and Clean Air (CREA).

Figure 11. Air pollution-related deaths by year and by scenario

Corresponding with the slow phase-out of power plants, deaths are expected to reduce slowly after peaking in the late 2020s. Air pollution would continue to burden society beyond 2050 if Indonesia continues with its current policies. With an opportunity to accelerate coal phase-out by 2040, the country should prioritise cancellation of the coal power plants that are planned but not yet under construction and replace coal capacity needs with renewable sources. These measures would kick-start national efforts in a Just Transition. As illustrated in Figure 11, air pollution-related deaths and costs would reach an earlier peak in 2026, followed by a rapid decline to reach zero in both deaths and economic costs by 2041 under the 1.5 degrees scenario.

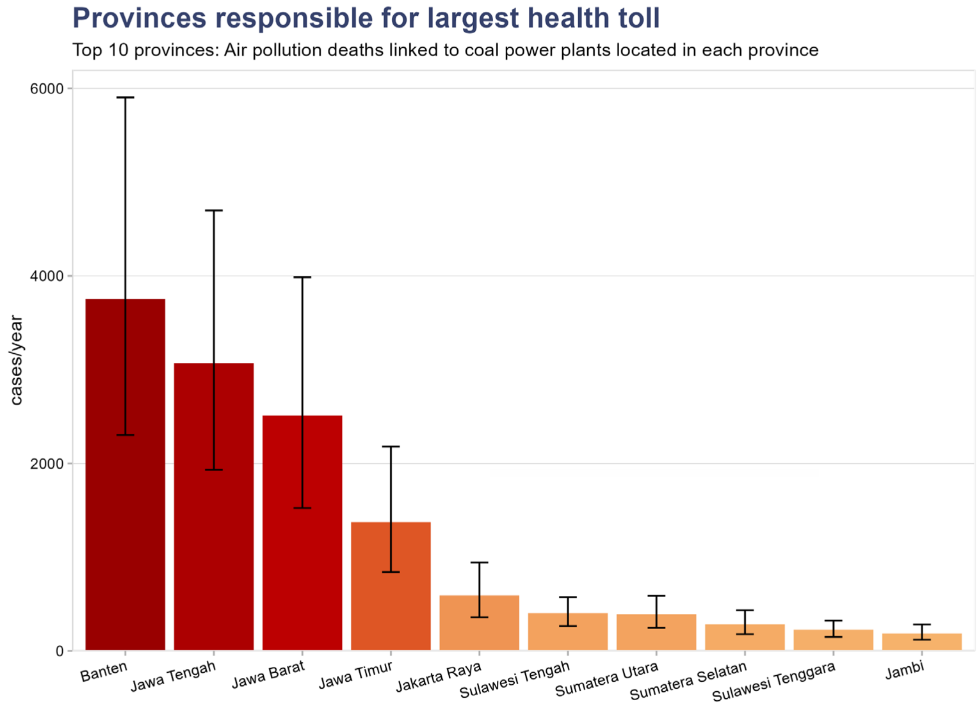
The magnitude of deaths linked to air pollution from coal power plants at the provincial level is illustrated in Figure 12. West Java (Jawa Barat) is the most affected province by coal-fired power emissions with annual deaths exceeding 4,000 (95% CI: 2,566–6,438). West Java is followed by Banten with 2,000 (95% CI: 1,308–3,406) deaths per year, and Central Java (Jawa Tengah) with 1,700 (95% CI: 1,090–2,749) annual deaths.



Source: Centre for Research on Energy and Clean Air (CREA).

Figure 12. Top 10 provinces most affected by coal power emissions

Figure 13 shows the estimates of air pollution deaths attributed to the provinces where the coal power plants are located. Provinces whose emissions are responsible for the greatest of annual deaths are Banten, Central Java (Jawa Tengah), and West Java (Jawa Barat). Banten's CFPPs can be linked to an estimated 3,800 deaths, while air pollutant emissions from CFPPs located in Central Java and West Java cause an estimated 3,000 and 2,500 annual deaths, respectively. These major provinces located on the island of Java, have the largest capacity-wise and the highest count of coal-fired power plants in all of Indonesia.

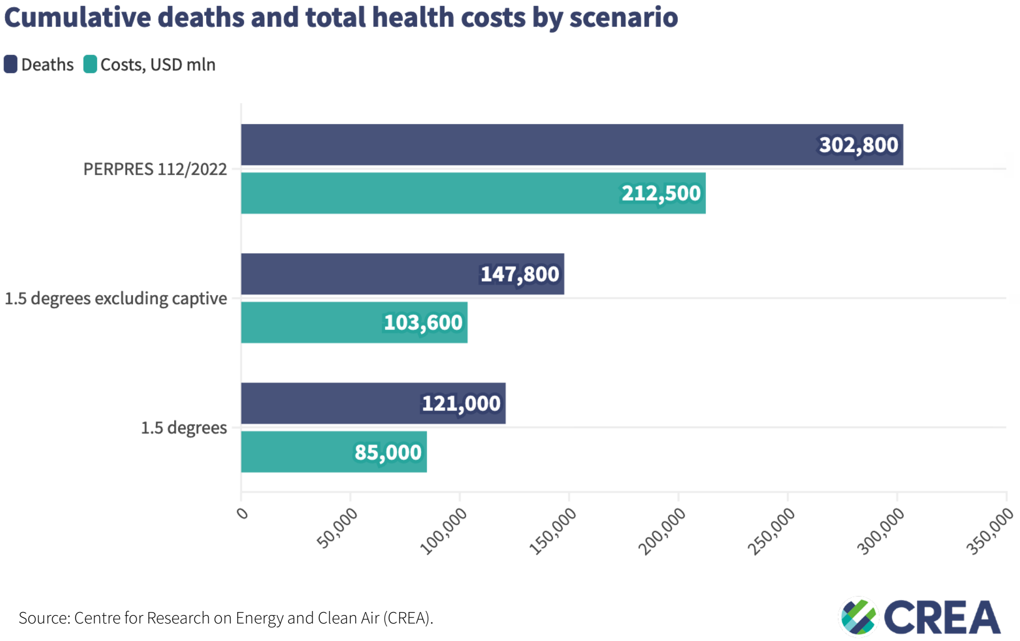


Source: Centre for Research on Energy and Clean Air (CREA).

Figure 13. Top 10 provinces responsible for the largest number of deaths per year

Cumulative impacts

As illustrated in Figure 14, the cumulative deaths would reach nearly 303,000 deaths from 2024 till all plants reach the end of their life (95% CI: 188,700–498,000) under the current policies. All health costs would amount to USD 212 billion (IDR 3.2 quadrillion; 95% CI: USD 132.5–327.9 billion, IDR 2.0–4.9 quadrillion). The 1.5 degrees scenario that excludes captive plants would lead to significantly lower deaths and health costs, with cumulative deaths halved at 148,000 (95% CI: 91,400–231,000). The economic burden to society would also halve at USD 104 billion (IDR 1.5 quadrillion; 95% CI: USD 63.7–161.2 billion, IDR 0.9–2.4 quadrillion). If captive power plants were to be retired early by 2040, greater national benefits can be achieved. Approximately 180,000 air pollution-related deaths and USD 127 billion (IDR 1.9 trillion) in health costs can be avoided.



Source: Centre for Research on Energy and Clean Air (CREA).

Figure 14. Cumulative deaths and health costs from 2024 onwards by scenario

Air pollution has a particularly profound impact on newborns, causing low birth weight, premature births and asthma to name a few. In adults, health impacts include diabetes, stroke and chronic obstructive pulmonary disease. These give rise to work absences due to the need to take sick leave or care for someone else who is sick and this burdens any economy.

The estimated cumulative health impacts are significant under the current policy. A large extent could be avoided through better alignment with the 1.5 degrees target. As shown in Table 5, the 1.5 degrees scenario would avoid over half the number of sick leave days, new cases of asthma in children, total cases of children suffering from asthma due to pollution exposure, asthma emergency room visits, low birthweight births, and preterm births compared to the PERPRES 112/2022 scenario. For instance, the number of children suffering from asthma due to pollution exposure would decrease from 240,323 to 107,494. Meanwhile, the 1.5 degrees scenario that excludes captive coal plants from the retirement assumption would still bring significant reduction to 120,091, less than half of the number of cases estimated in the PERPRES 112/2022 scenario.

Similarly, the calculated years of lives lost due to NO_2 and SO_2 exposure are significantly reduced in the 1.5 degrees scenarios compared to the PERPRES 112/2022 scenario. The greatest improvements would be in the years of lives lost from SO_2 exposure, as the 1.5 degree scenario would reduce years of lives lost by 59%. The reduction in the years of lives lost due to NO_2 exposure would also be significant, at 58%. Excluding captive plants from the 1.5 degrees scenario would lead to about 10% smaller reductions.

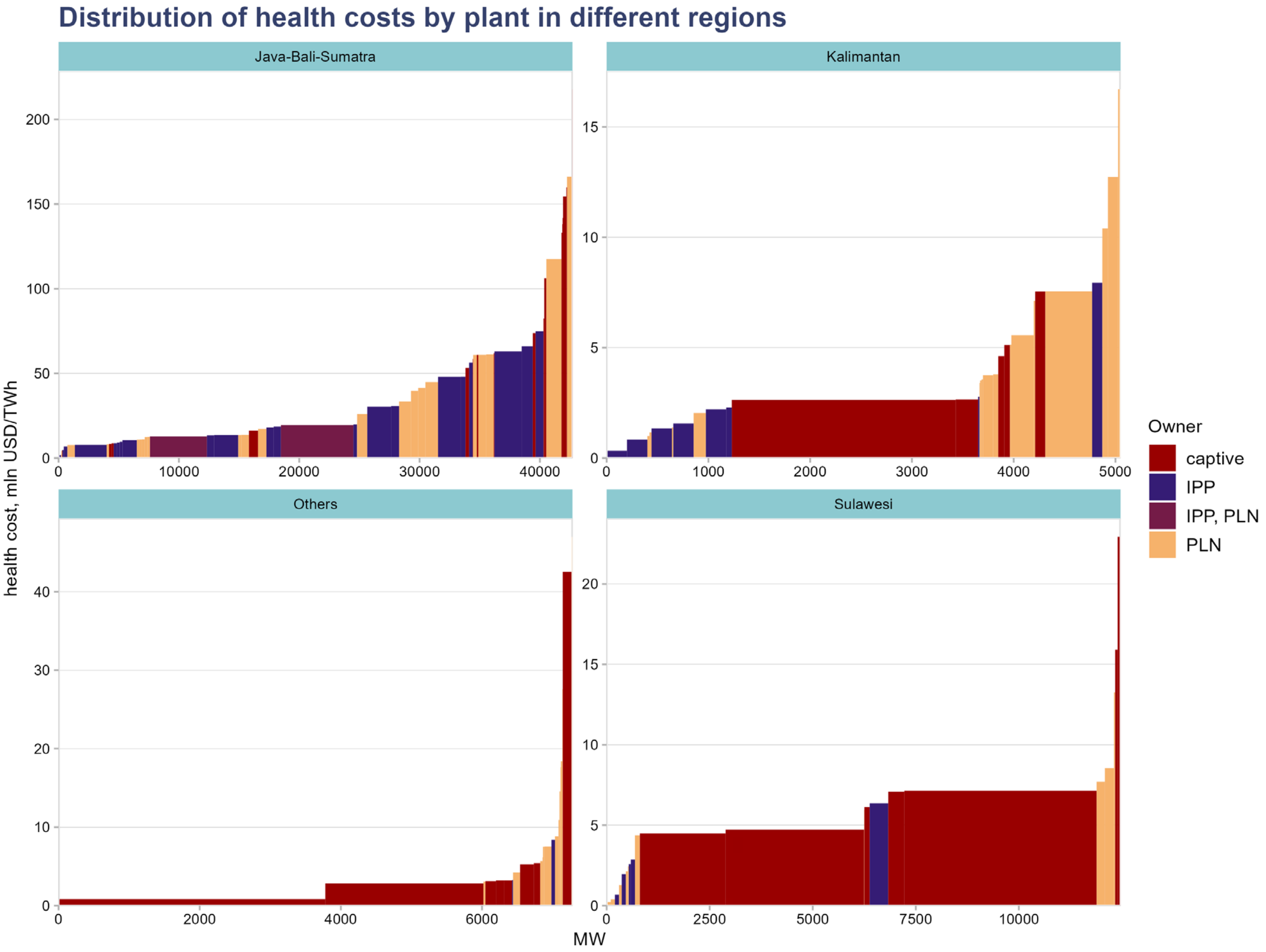
When it comes to the years lived with disabilities, the scenarios aligning with the 1.5 degrees target — including optimised captive power plant retirement — would reduce those years by as much as 60–70%. The years lived with chronic obstructive pulmonary disease, diabetes, or stroke would reduce by more than a half in the 1.5 degrees excluding captive scenario, but the reduction would be even higher in the 1.5 degrees scenario.

Table 5. Central estimate of cumulative health impacts by scenario

Outcome	1.5 Degrees	1.5 degrees excluding captive	PERPRES 112/2022
Counts of sick leave days			
Work absence	48,831,083	55,968,109	114,352,550
Number of cases			
New cases of asthma in children	70,689	82,869	146,902
Total cases of asthma in children	302,495	354,636	628,652
Asthma emergency room visits	107,494	120,091	240,323
Low birthweight births	34,273	38,396	73,539
Preterm births	50,514	55,753	107,180
Years of lives lost			
All causes from NO_2 exposure	645,845	795,756	1,521,544
All causes from SO_2 exposure	403,125	501,943	974,158
Years lived with disability			
Chronic obstructive pulmonary disease	41,169	48,772	103,933
Diabetes	27,341	40,479	82,491
Stroke	87,160	101,923	217,926

Benefits of prioritising plants with worst health impacts

There is wide variation in health impacts per unit of electricity generated between different coal-fired power plants in Indonesia, owing to differences in plant location and emission intensity of the plants. Figure 15 illustrates the variance in health costs distribution across the region of Java-Bali-Sumatra, Kalimantan, Sulawesi, and others based on CFPP ownership categories, namely PLN, IPP, combination of PLN and IPP, and captive. Across Java-Bali-Sumatra, impacts are nearly exclusively attributed to PLN and IPP. In the remaining regions, particularly Sulawesi and other regions, captive power plants would be the primary contributors to air pollution from coal power. As for Kalimantan, considerable contributions are apparent from both captive and PLN-owned power plants.



Source: Centre for Research on Energy and Clean Air (CREA).

Figure 15. Distribution of health costs by plant in different regions

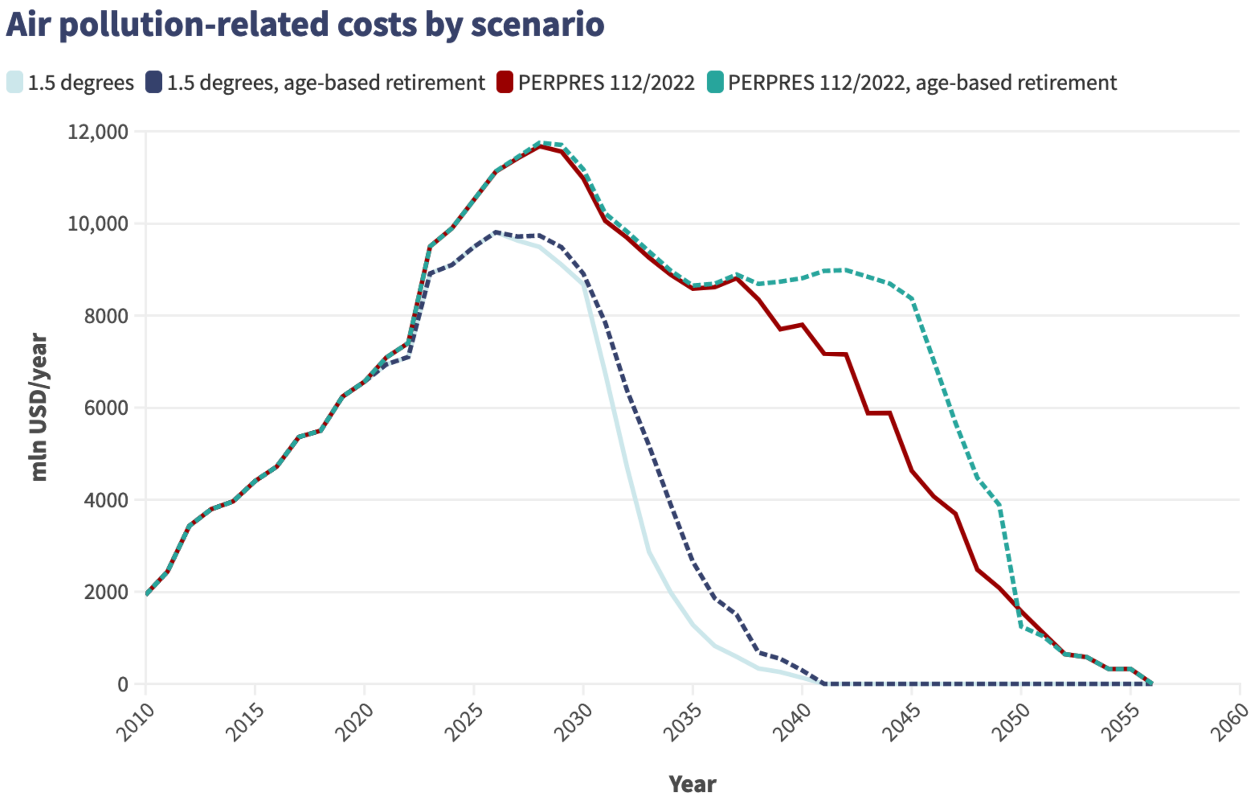
The plants with the highest health costs are ones located in or near densely populated areas, with meteorological conditions that lead to high exposure of the population to the plant emissions, e.g. due to prevailing wind directions, and poor emission control performance. Clear examples are the PLN Muara Karang and Lontar power plants located in Jakarta and Tangerang, as well as the captive coal power plants located in Bekasi, Karawang, Purwakarta, and Bandung. A full list of CFPPs is provided in Table 6 below where the coal power plants are ranked from the highest to the lowest health cost per unit of electricity generated in each region.

Table 6. Coal power plants ranked from the highest estimated health costs per unit of electricity generated in each grid region, separated into utility and captive power plants

Coal Power Plant	Coal Province Plant	Region	Owner	Capacity (MW)
Muara Karang	Jakarta Raya	Java-Bali-Sumatra	PLN	400
Lontar	Banten	Java-Bali-Sumatra	PLN	1,260
Cirebon	Jawa Barat	Java-Bali-Sumatra	IPP	660
Jawa-1 / Cirebon-2	Jawa Barat	Java-Bali-Sumatra	IPP	924
Cilacap	Jawa Tengah	Java-Bali-Sumatra	IPP	2,260
Atambua	Nusa Tenggara Timur	Others	PLN	24
Parit Baru Expansion	Kalimantan Barat	Kalimantan	PLN	100
Pantai Kura-Kura	Kalimantan Barat	Kalimantan	PLN	55
Embalut	Kalimantan Timur	Kalimantan	IPP	100
Asam-Asam	Kalimantan Selatan	Kalimantan	PLN	460
Sumbawa Barat	Nusa Tenggara Barat	Others	PLN	14
Rote Ndao	Nusa Tenggara Timur	Others	PLN	6
Bima	Nusa Tenggara Barat	Others	PLN	20
Alor	Nusa Tenggara Timur	Others	PLN	6
Ropa	Nusa Tenggara Timur	Others	PLN	14
Nii Tanasa	Sulawesi Tenggara	Sulawesi	PLN	30
Punagaya	Sulawesi Selatan	Sulawesi	PLN	220
Sulsel Barru	Sulawesi Selatan	Sulawesi	PLN	200
Jeneponto	Sulawesi Selatan	Sulawesi	IPP	450
Talaud	Sulawesi Utara	Sulawesi	PLN	6
FAJAR power station	Jawa Barat	Java-Bali-Sumatra	captive	55
Pindo-Deli-Ii power station	Jawa Barat	Java-Bali-Sumatra	captive	50
Cikarang Babelan power station	Jawa Barat	Java-Bali-Sumatra	captive	280

Indo Bharat Rayon power station	Jawa Barat	Java-Bali-Sumatra	captive	36.6
Bandung Indosyntec power station	Jawa Barat	Java-Bali-Sumatra	captive	30
Bengkayang Power Station	Kalimantan Barat	Kalimantan	captive	100
Kalimantan Cement Works power station	Kalimantan Selatan	Kalimantan	captive	55
Tabalong Wisesa power station	Kalimantan Selatan	Kalimantan	captive	60
Ketapang Smelter power station	Kalimantan Barat	Kalimantan	captive	220
Adaro Aluminum Smelter power station	Kalimantan Timur	Kalimantan	captive	2,200
Batu Hijau power station	Nusa Tenggara Barat	Others	captive	124
East Halmahera power station	Maluku Utara	Others	captive	90
Amamapare Port power station	Papua	Others	captive	195
MSP Pulau Obi power station	Maluku Utara	Others	captive	114
Xinxing Ductile Iron Pipes Co Captive power station	Maluku Utara	Others	captive	114
Tonasa Cement Plant power station	Sulawesi Selatan	Sulawesi	captive	70
Pomalaa Nickel power station	Sulawesi Tenggara	Sulawesi	captive	60
Delong Nickel	Sulawesi Tengah	Sulawesi	captive	4,665
Qingdao Zhongsheng captive power station	Sulawesi Tengah	Sulawesi	captive	390
Wanxiang Nickel Indonesia power station	Sulawesi Tengah	Sulawesi	captive	130

Retirement pathways developed in the 1.5 degrees scenarios prioritise the plants with the highest health impacts. This greatly increases the health benefits and cost-effectiveness of the coal phase-out. If the logic of retiring the oldest plants first were to apply, the number of air pollution-related deaths in the current policies scenario would increase by 36,000 cases. Health cost trends are shown in Figure 16, where the dashed lines represent the higher costs that can be attributed to age-based retirement in both the 1.5 degrees scenario and the PERPRES 112/2022 scenario. Cumulative health costs would increase by USD 12 billion (IDR 180 trillion) higher from the optimised health-based retirement schedule developed for the 1.5 degrees scenario, and by USD 24 billion (IDR 360 trillion) higher from the PERPRES 112/2022 scenario.



Source: Centre for Research on Energy and Clean Air (CREA).

Figure 16. Air pollution-related costs by scenario with age-based retirement.

Evaluation of air pollution control implementation

In contrast to the minor benefits of co-firing, air pollution control can have a large impact on the economy, public health, resilience, sustainability, and above all, the air quality of Indonesia and its population. Further concrete actions are needed to sustain the momentum started in the Transparent Pollution Control project (EEAS, 2021) and best align national efforts and international support for the benefit of all Indonesian people.

The country needs to enforce stronger and actionable national planning to better address ongoing air pollution issues by shifting away from the use of coal as an energy source. As reported by IQAir, residents of many major cities in Java and other highly polluted metropolitan areas of Indonesia are exposed to unhealthy levels well above the WHO thresholds throughout the year (IQAir, 2023). While immediate restricting actions on coal energy generation at the national level would bring significant reduction in coal power emissions, the consideration for proper installation of air pollution control technology is essential during the coming decades. Between now and 2030, trajectories of power generation capacity and the associated health impacts are expected to still move upward before reaching the peak and decreasing.

Based on this consideration, we included an additional analysis to the main three scenarios presented in the previous chapter. We quantified the health and economic impacts of the current PERPRES 112/2022 scenario with air pollution control technology and the 1.5 degrees scenario with air pollution controls implemented. The tabulation of the assumptions is provided in Table 7. In the scenarios where air pollution control is implemented, new coal power plants are assumed to be equipped with efficient air pollution control technology by 2026 and existing plants by 2030. This assumption was not applied to those existing plants that are scheduled to retire by 2035.

Table 7. Scenario matrix of APC assumptions in the two main scenarios - PERPRES 112/2022 and 1.5 degrees

Scenario	PLN & IPP Retirement Schedule	Captive Power Retirement Schedule	Biomass Co-firing	Air Pollution Control Retrofit
PERPRES 112/2022 - referred to as current policies in this study	**14 GW of PLN & IPP** power plants are retired by **2035**, while the **remaining** are retired by **2050**	All captive power plants are retired after 30 years of operation	Phased increase of co-firing share, reaching **20% at PLN power plants by 2030**	APCs are installed to **follow the current national emission limits** until end-of-life
PERPRES 112/2022, with APC				**New plants are required to install efficient SO_2, NO_x and dust controls by 2026 and existing plants by 2030, unless they retire by 2035**
1.5 degrees	Retirement schedule aligned with **IESR-UMD optimised pathway**	Retirement schedule aligned with **IESR-UMD optimised pathway**	Co-firing maintained at currently committed levels, i.e. **5% at most PLN power plants**	APCs are installed to **follow the current national emission limits** until end-of-life
1.5 degrees, with APC				**New plants are required to install efficient SO_2, NO_x and dust controls by 2026 and existing plants by 2030, unless they retire by 2035**

We referred to the European Union Best Available Technique Reference Document (BREF) as the benchmark for efficient air pollution controls (European Commission, 2017). This document specifies a range of emission levels that are consistent with the use of best available air pollution control techniques. We applied the higher (more lenient) end of the ranges, which is the level that all power plants in the EU are legally required to meet. Therefore, there is a lot of experience of retrofitting existing coal-fired power plants to meet the standards. In the case of the EU, existing power plants are generally much older than those in Indonesia.

Table 8. Air Pollution Control installation costs in the "current policies with APC" scenario

Description	Value		Unit	
Capacity retrofit with APC	43,440		MW	
Newbuild capacity with APC	5,450		MW	
Total investment cost	6,936	102,997	mln USD	bln IDR
Total operating cost, per year (2035)	684	10,150	mln USD	bln IDR
Total operating cost, from installation year to end-of-life	13,569	201,491	mln USD	bln IDR
Health cost avoided in 2035	5,828	86,546	mln USD	bln IDR
Total health costs avoided, from installation year to end-of-life	90,441	1,343,037	mln USD	bln IDR
Net economic benefit	69,937	1,038,549	mln USD	bln IDR

Approximately 8,000 deaths in 2035 alone could be avoided if the current policies scenario would include the installation of proper APC, as well as USD 5.8 billion (IDR 86.5 trillion) in air pollution-related health costs. In cumulative terms, a total of 129,000 deaths and health costs of USD 90 billion (IDR 1.3 quadrillion) could be avoided if coal power plants were required to install efficient dust, NO_x, and SO_2 controls.

Installing APC is highly profitable from the point of view of the whole society. Health costs that are saved significantly outweigh the implementation costs of air pollution control. We project net economic savings to the society of USD 70 billion (IDR 1.1 quadrillion) in the current policies scenario with APC installation, compared with current policies with no improvements in APC requirements. The analysis has taken into account the investment and operating costs of the APC. Further details on the costs for the APC technologies considered in this study are provided in Tables A4 and A5 in the Appendix .

Compared to the more significant impacts that would result from delayed coal phase-out in the PERPRES 112/2022 scenario, the avoided deaths and costs between the 1.5 degrees scenario and the 1.5 degrees scenario with APC installation are relatively small. This is mainly due to the fact that most coal power plants were assumed to retire by 2035 in the 1.5 degrees pathway, and therefore not required to further improve their APC under our assumptions. Furthermore, our analysis shows that the required investment and operating costs of the APC remain low, and the installation of improved APC is beneficial from a cost-benefit perspective. The 1.5 degrees scenario with APC has by far the lowest air pollution-related deaths, as well as costs and other health impacts. Tabulation of health impacts and costs is provided in Tables A1 and A2 in the Appendix.

Table 9. Deaths and costs in 2035 in different scenarios

2035		
Scenario	Deaths	Costs, USD mln
PERPRES 112/2022	12,216	8,586
PERPRES 112/2022 w/ APC	**3,931**	**2,758**
1.5 degrees	1,792	1,285
1.5 degrees w/ APC	**1,119**	**808**

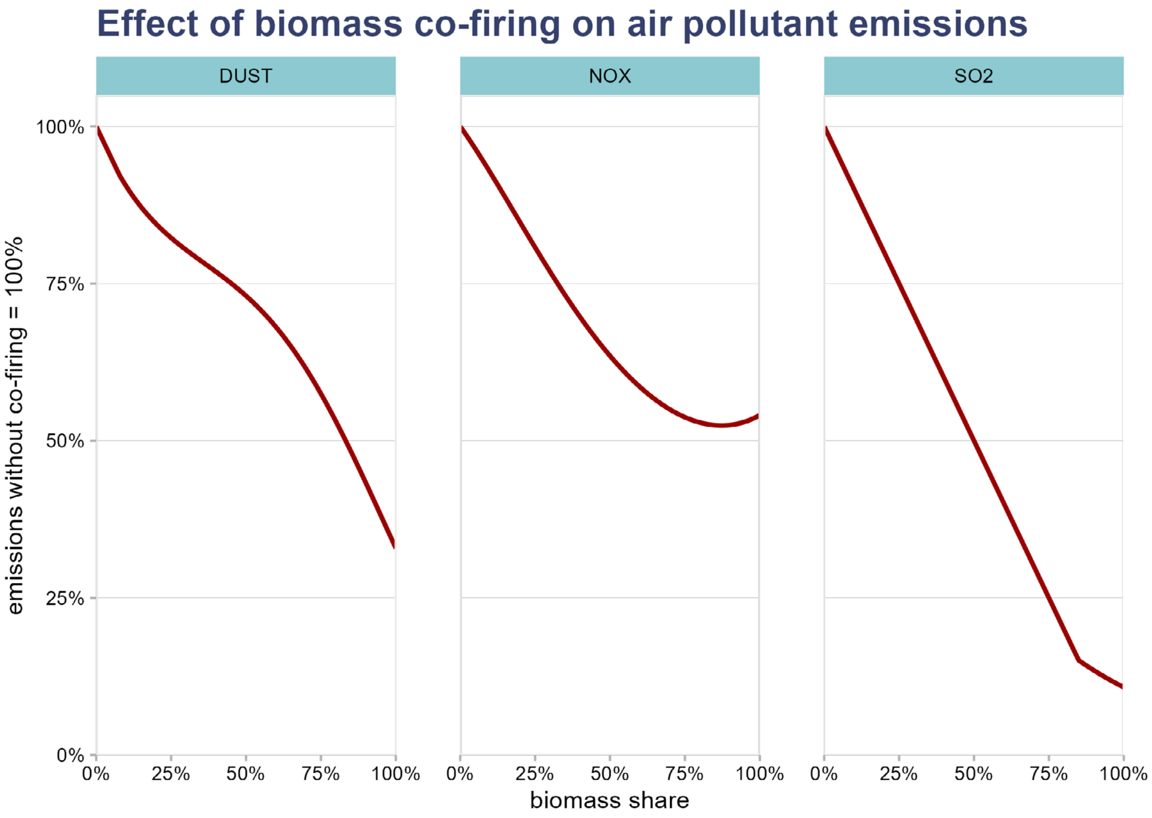
Table 10. Cumulative deaths and costs from 2024 onwards in different scenarios

Cumulative		
Scenario	Deaths	Costs, USD mln
PERPRES 112/2022	302,800	212,500
PERPRES 112/2022 w/ APC	**174,200**	**112,100**
1.5 degrees	121,000	85,000
1.5 degrees w/ APC	**115,800**	**81,400**

Evaluation of co-firing implementation

While co-firing biomass can reduce emissions of air pollutants to a degree, it is no solution to Indonesia's air pollution challenge. We project that raising the share of co-firing to a minimum of 20% at all PLN power plants — a major challenge in terms of the availability of biomass and potentially also a technical challenge — has little to virtually no impact on the emissions of air pollutants from coal power plants.

Figure 17 below shows the effect of different biomass shares on PM, NO_x, and SO_2 emissions. While pollutant emissions show noticeable reductions at higher biomass shares, PLN's current target of 10% biomass share would deliver only a 9% emission reduction in particulate matter, about 7% in NO_x and 10% in SO_2 at power plants where it is applied. The effect on emissions is derived from a large dataset comprising hundreds of combustion plants, making it representative of the aggregate effect, even considering variation between individual plants.



Source: Centre for Research on Energy and Clean Air (CREA) analysis based on European Environment Agency (EEA) data.

CREA

Figure 17. Correlation between biomass share and emissions for dust, NO_x, and SO_2

CREA's analysis shows that merely 1.5–2.4% reduction, depending on the pollutant, can be expected in Indonesia's total coal power plant emissions as a result of co-firing, when co-firing is limited to PLN power plants. In contrast, requiring efficient emission control technology installations in all plants operating beyond 2035 would effectively reduce emissions of SO_x by an estimated 73%, NO_x by 64%, dust by 86%, and mercury by 71%.

As part of PLN's Green Booster program, biomass co-firing is expected to account for about 3.6% out of the 23% renewables share in 2023 as defined in RUPTL 2021–2030 (OECD, 2021). PLN estimates an average of 10.2 million tonnes of biomass to be supplied annually to substitute 12% of coal use (PLN, 2023). In 2022, PLN was able to realise 0.455 million tonnes of biomass supply, from sawdust (90%), woodchips (3%), palm shells (5%), and other biomass feedstock (2%). Supply targets will ramp up to 2.2 million tonnes in 2023, 2.83 million tonnes in 2024, and will reach 10.2 million tonnes by 2025 (IESR, 2022b).

The Indonesian Biomass Energy Society (Masyarakat Energi Biomassa Indonesia) stated that PLN's achievement of implementing biomass co-firing in 36 CFPPs is encouraging. However, questions must be raised about the sources for the long-term supply of biomass. In addition, global prices of biomass feedstock, particularly wood pellets, are getting higher. The market for exports as well as non-energy domestic use increasingly becomes more attractive for domestic suppliers. Currently, the sales price for co-firing feedstock is capped at USD 70 (IDR 1 million) per tonne, while the price could reach USD 240 (IDR 3.6 million) per tonne if sold to Japan or Korea (MEBI, 2023; IESR, 2022b).

PLN claims that biomass co-firing would reduce up to 11 million tons of CO2 and other greenhouse gases (PLN, 2023). However, PLN has not considered unaccounted impacts on emissions that may arise due to technical and economic barriers associated with the biomass feedstock supply chain. The implementation of biomass co-firing will not substantially reduce GHG emissions if coal remains the major fuel source for Indonesia's coal fleet.

Furthermore, in addition to financial risks associated with poor fuel economy and operational constraints, there are risks of derating the asset. As noted by Institute for Energy Economics and Financial Analysis (IEEFA), Indonesia must take prudent steps to ensure the feasibility of co-firing adoption, particularly considering the predominance of pulverised coal boilers in PLN's coal fleet, which have a considerably narrow tolerance range in fuel properties (IEEFA, 2021b).

In order to meet the economic equivalent of coal, options for feedstock sources are limited by distance, namely 360 km for Java, 300 km for Sumatra, Kalimantan, and Sulawesi, and 187 km for Maluku and Papua. Even though transportation costs are limited to 11% of the capped price, supply risks may be greater than anticipated. IESR also noted that the actual cost required to implement biomass co-firing is likely higher since costs associated with boiler fouling and equipment upgrade and/or adjustment needs are excluded (IESR, 2022b).

While biomass co-firing is already being implemented in many PLN power plants, there are also future aspirations for co-firing ammonia. There are multiple obstacles to sourcing this ammonia — above all the cost and greenhouse gas emission benefits that are questionable even at best (Kennedy et al., 2023; BloombergNEF, 2022). In addition, recent CREA research has found that ammonia co-firing at coal-fired power plants could lead to very significant fugitive ammonia emissions both from the ships transporting ammonia and from the power plant stacks (Myllyvirta and Kelly, 2023). Ammonia reacts with SO_2 and NO_2 in the atmosphere to form $PM_{2.5}$ aerosols. Therefore, ammonia co-firing could, in fact, make the air quality impacts of coal-fired power plants worse than they currently are.

In this study, CREA assumes two variations of the biomass co-firing scheme; (1) phased increase of co-firing share, reaching 20% at PLN power plants by 2030 for PERPRES 112/2022 scenario, (2) currently achieved share of 5% biomass co-firing for most PLN CFPPs to be maintained and not increased for the 1.5 degrees scenario. Such consideration was made based on the conclusion that biomass co-firing is not an effective strategy that would bring meaningful long-term contributions to Indonesia's targets to realise the climate commitments and achieve an inclusive and just transition (Prasetiyo et al., 2023).

Conclusion

Indonesia has started to lay down the groundwork for the retirement of its CFPPs as defined in Presidential Regulation No. 112 Year 2022 on the Acceleration of Renewable Energy Development for the Provision of Electricity. With the national government committing to finalise the road map within six months since the formation of the JETP Secretariat in February 2023, Indonesia is now entering a critical period where commitments are turned into actions to get on track towards the 1.5 degrees path. The highly anticipated roadmap detailed in the Comprehensive Investment Plan and Policy (CIPP) marks the beginning of clean energy investment mobilisation in Indonesia.

In this analysis, CREA seized the opportunity for the first assessment of the consequences of the stipulated coal phase-out timelines, the presence of Air Pollution Control systems in coal power plant operations, and the implementation of biomass co-firing as part of PLN's green transition strategy. CREA has developed a comprehensive health impact assessment that outlines the implications of Indonesia's decisions on coal power generation plans. Scenario pathways were built based on the best data available, centered around the aim for a Just Energy Transition that prioritises the lives and livelihoods of the affected communities throughout the journey. Indonesia would be able to minimise health impacts on the affected population by prioritising early retirement of coal power plants and deploying renewables instead of pursuing solutions that prolong coal power plant operations, particularly co-firing with biomass and ammonia.

While the current burden of air pollution from coal power plants on the health of Indonesians and on the economy is overlooked and undercounted, CREA projects the planned expansion up to 2030 to sharply increase this existing burden. The analysis shows a significant increase of 110% in air pollutant emissions over the past decade, solely from coal power generation. CREA estimates that coal power emissions in 2022 were responsible for 10,500 deaths from air pollution and USD 7.4 billion (IDR 109.9 trillion) of economic burden from the associated health impacts. Under the implementation of current policies by 2030 and the full operation of all CFPPs currently planned, Indonesian people will be exposed to 70% higher air pollutant emissions. As Indonesia increases its coal generation capacity from 45 GW currently to 63 GW before peaking in 2028, annual deaths linked to air pollution from coal power will rise to 16,600 per year and the health economic burden will reach USD 11.8 billion (IDR 175.2 trillion) per year.

Cancellation of new coal power projects and acceleration of the schedules of the retirement of existing plants would avoid significant economic costs that can cover the investment costs needed to deploy clean and renewable energy. A faster coal phase-out by 2040, in line with the 1.5 degrees target of the Paris Agreement, would avoid a cumulative total of 182,000 air pollution-related deaths and relieve health economic burden of USD 130 billion (IDR 1.9 quadrillion) up to 2060. As highlighted by IESR and UMD, the investment for renewable energy and energy efficiency must reach USD 135 billion (IDR 2 quadrillion) total investment by 2030, additional USD 455 billion (IDR 6.8 quadrillion) by 2040, and additional USD 633 billion (IDR 9.4 quadrillion) by 2050 to facilitate the retirement pathway that is aligned with the 1.5 degrees commitment (Cui et al., 2022).

Indonesia's retirement schedule for coal phase-out should include a nationwide evaluation of plant-level health impacts for the amount of electricity the plant generates. The basis for this consideration is to ensure equitable energy transition and mitigate impacts on the immediately affected communities living in close proximity and all citizens of Indonesia. CREA has generated a list of power plants that should be prioritised, ranked from highest health costs for being located in or near densely populated areas, with the surrounding meteorological conditions that raise exposure, and for plants assumed to be operated with poor emission control. Clear examples of such units include the PLN's Muara Karang and Lontar power plants located in Jakarta and Tangerang, as well as several captive coal power plants located in Bekasi, Karawang, Purwakarta, and Bandung.

Full inclusion of the large fleet of captive power plants in Indonesia's coal phase-out policies is crucial from both greenhouse gas and public health perspective. Captive power plants are shown to be responsible for approximately 20% of the total health impacts of coal power generation in Indonesia. Any room for ambiguity in the regulatory framework may leave captive power plants outside the 2040 coal phase-out policy. CREA approximates an additional annual health burden of 27,000 air pollution-related deaths and health costs of USD 20 billion (IDR 300 trillion) to be attributed to captive plants alone.

Even as coal power plants begin to retire, investing in improved air pollution controls in those power plants that plan to operate well into and beyond 2030 would deliver substantial benefits. The country can avoid 8,300 deaths and USD 5.8 billion (IDR 86 trillion) in health costs in 2035 with the proper installation of APCs, our analysis shows. Taking into account the investments and operational costs associated with APC facilities, the country would still gain a net economic benefit of USD 70 billion (IDR 1 quadrillion) by mitigating public health risks from coal power emissions.

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Appendix

Table A1. Cumulative deaths and total health costs of each scenario

Scenario	Deaths*	Costs, USD bln	Costs, IDR tln
1.5 degrees w/ APC	115,800 (71,600 – 180,700)	81.4 (50.0 – 126.5)	1,208.2 (742.6 – 1,877.8)
1.5 degrees	121,000 (74,940 – 188,400)	85.0 (52.3 – 131.9)	1,262.6 (777.3 – 1,985.8)
1.5 degrees excluding captive	147,800 (91,400 – 231,000)	103.6 (63.7 – 161.2)	1,539.1 (946.0 – 2,394.1)
PERPRES 112/2022 w/ APC	174,200 (107, 200 – 273,600)	122.1 (74.7 – 191.1)	1,813.2 (1,110.0 – 2,837.5)
PERPRES 112/2022	302,800 (189,000 – 468,000)	212.5 (131.5 – 327.9)	3,156.2 (1,953.5 – 4,868.8)

**95% confidence interval in parentheses*

Table A2. Cumulative health impacts by scenario

Outcome	Value	Scenario				
		1.5 degrees w/ APC	1.5 degrees	1.5 degrees excluding captive	PERPRES 112/2022	PERPRES 112/2022 w/ APC
Work absence (sick leave days)	central	**46,791,822**	**48,831,083**	**55,968,109**	**114,352,550**	**67,204,753**
	low	39,819,025	41,554,40	47,627,885	97,312,027	57,190,074
	high	56,713,477	156,054,396	64,247,163	131,268,092	77,145,981
New cases of asthma in children	central	**68,857**	**70,689**	**82,869**	**146,901**	**101,438**
	low	15,826	16,248	19,048	33,765	23,316
	high	150,010	154,004	180,534	320,036	220,992
Number of children suffering from asthma due to pollution exposure	central	**294,650**	**302,495**	**354,636**	**628,652**	**434,079**
	low	78,711	80,805	94,736	167,929	115,958
	high	598,326	614,265	720,132	1,276,610	881,452
Asthma emergency room visits	central	**103,638**	**107,494**	**120,091**	**240,323**	**146,453**
	low	62,304	64,635	72,263	145,096	88,209
	high	144,532	149,898	167,411	334,555	204,080

Outcome	Value	Scenario				
		1.5 degrees w/ APC	1.5 degrees	1.5 degrees excluding captive	PERPRES 112/2022	PERPRES 112/2022 w/ APC
Low birthweight births	central	**32,997**	**34,273**	**38,396**	**73,539**	**45,590**
	low	10,267	10,664	11,947	22,882	88,209
	high	57,103	59,310	66,446	127,261	204,080
Preterm births	central	**48,841**	**50,514**	**55,753**	**107,180**	**67,458**
	low	23,729	24,542	27,086	52,072	32,774
	high	51,844	53,621	59,181	113,770	71,607
Years of lives lost						
All causes from NO_2 exposure	central	**628,415**	**645,845**	**795,756**	**1,521,544**	**997,891**
	low	268,147	275,579	295,555	649,202	425,799
	high	1,445,900	1,486,038	1,593,681	3,501,181	2,296,049
All causes from SO_2 exposure	central	**393,978**	**403,125**	**501,943**	**974,158**	**567,595**
	low	233,632	239,054	242,012	577,673	336,588
	high	593,450	607,235	614,736	1,467,413	854,973
Years lived with disability						
Chronic obstructive pulmonary disease	central	**39,202**	**41,169**	**48,772**	**103,933**	**58,159**
	low	14,243	14,957	14,515	37,759	21,131
	high	73,000	76,663	74,394	193,546	108,302
Diabetes	central	**24,407**	**27,341**	**40,479**	**82,491**	**37,501**
	low	4,638	4,963	4,789	13,375	7,022
	high	56,578	63,993	60,287	205,985	89,059
Stroke	central	**83,273**	**87,160**	**101,923**	**217,926**	**123,320**
	low	26,850	28,104	27,326	70,272	39,763
	high	170,836	178,807	173,866	447,049	854,973

Table A3. Top 10 provinces most affected by coal power emissions and top 10 provinces most responsible for the largest number of deaths per year

Province	Deaths in the province	Caused deaths by the province
Jawa Barat	4,135 (2,566 – 6,438)	2,510 (1,524 – 3,987)
Banten	2,153 (1,308 – 3,406)	3,755 (2,304 – 5,905)
Jawa Tengah	1,761 (1,090 – 2,749)	3,069 (1,932 – 4,698)
Jakarta Raya	1,643 (991 –2,634)	593 (360 – 944)
Jawa Timur	1,013 (611 – 1,642)	1,374 (842 – 2,180)
Lampung	636 (408 – 947)	90 (52 – 151)
Sumatera Utara	356 (224 – 537)	390 (246 – 588)
Sumatera Selatan	254 (163 – 380)	283 (179 – 434)
Sulawesi Tenggara	241 (159 – 344)	226 (149 – 323)
Sulawesi Selatan	241 (158 – 349)	73 (48 – 107)
Jambi	107 (69 – 159)	187 (119 – 284)

Table A4. Cost information compiled for different air pollutant control technologies

Country	Controlled pollutant	Control technology	Capital cost, original, USD/kW (2022)	Capital cost, transferred to Indonesia		O&M cost, original, USD/MWh (2022)	O&M cost, transferred to Indonesia		Reference
				USD/kW (2022)	IDR/W (2022)		USD/MWh (2022)	IDR/kWh (2022)	
USA	NOx	SCR	148	130	2,193				EPA (2019)
USA	NOx	SNCR	26	23	380	1.2	1.0	17.4	EPA (2017)
USA	PM	ESP	26	18	380	0.3	0.2	4.2	EPA (2003)
India	SO2	FGD	101	62	1,505	1.4	1.0	21.5	Cropper et al. (2019)
India	SO2	FGD	75	51	1,119				Srinivasan et al. (2018)
India	SO2	FGD	53	36	784				Srinivasan et al. (2018)
China	SO2	FGD	51	32	760	2.2	1.5	32.2	Zhang & Liu (2014)
China	SO2	FGD	37	21	544	1.5	1.0	21.8	Sun et al. (2014)
USA	SO2	FGD	253	133	3,764	2.6	1.7	39.1	EIA (2022)
Thailand	SO2	FGD	49	36	729	0.5	0.5	7.7	Punyawadee et al. (2008)
Poland	SO2	FGD	203	109	3,021				IEEFA (2018)
Poland	SO2	FGD	209	112	3,104				IEEFA (2018)
Indonesia	SO2	FGD	87	71	1,299				Ferrari et al. (2019)
Indonesia	NOx	SCR	63	51	933				Ferrari et al. (2019)

Table A5. Total air pollutant control costs estimated for Indonesia

Control technology	Controlled pollutant	Capital cost, USD/kW (2022)	Capital cost, IDR/W (2022)	O&M cost, USD/MWh (2022)	O&M cost, IDR/kWh (2022)
FGD (limestone)	SO2	66	977	1.15	17.06
SCR	NOx	55	819	0.83	12.34
SNCR	NOx	23	3,345	0.83	12.34
ESP	PM	18	275	0.21	3.06
Total additional cost of meeting more stringent standards for newbuild power plants					
	all	73	1,081	0.57	8.46
Total additional cost for retrofits					
	all	148	2,201	1.98	29.40

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