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Research article

Transitioning from coal to solar: A cost-benefit analysis for sustainable power generation in Indonesia

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Abstract: The greenhouse gas (GHG) emissions contribution from power generation in Indonesia reaches 40% of the total GHG emissions in the energy sector because of the use of fossil fuels. The government aims to minimize GHG emissions in the power generation sector, one of which is the phase-out of coal power plants and replacing them with integrated photovoltaic (PV) power plants with battery energy storage systems (BESS). A cost-benefit analysis compared two development scenarios for 2023–2060. The base scenario continues developing coal power plants, and the phase-out scenario replaces coal power plants with integrated PV power plants and BESS. The analysis is solely focused on the financial costs and benefits for power plant investors. The results indicate that the present value of costs for the base scenario from 2023–2036 is initially lower compared to the phase-out scenario. However, in the long term, the costs of the phase-out scenario will gradually decrease and become more affordable. The benefit-cost ratio for the phase-out scenario is 2.36, while the base scenario is 2.12, indicating that the phase-out scenario is more prospective for future development. Additionally, the phase-out scenario has the advantage of achieving the net-zero emissions target by 2056 compared to the base scenario.

Keywords: cost-benefit analysis; coal power plant; energy transition; GHG-emissions; phasing-out

1. Introduction

The global pursuit of sustainable and cleaner energy sources has accelerated in recent decades due to concerns over climate change, air pollution, and the depletion of finite fossil fuel reserves [1]. Coal power plants, historically a cornerstone of global energy production, has come under scrutiny for its harmful environmental impacts and the need to transition to low-carbon alternatives [2]. Clean coal technologies have been explored to minimize the environmental impact of coal power plants [3]. Additionally, renewable energy and energy efficiency have been found to be negatively correlated with greenhouse gas (GHG) emissions, suggesting their potential as solutions to reduce air pollution [4,5]. The combustion of fossil fuels, including coal, leads to the emission of pollutants that impact air quality on local, regional, and global scales [6,7]. The urgent need for sustainable and environmentally friendly power generation has led to the phase-out of coal power plants [8]. Moreover, policies aimed at reducing GHG emissions can also have positive effects on reducing conventional pollutants that harm human health and the environment [9].

In line with global concern over the issue of global warming, the Indonesian government is committed to achieving the Paris Agreement targets. The agreements aim to keep the global temperature increase below 2 °C and strive to reach 1.5 °C, as well as achieve net-zero emissions by mid-century [10]. These targets were reaffirmed at the 26th United Nations Conference of the Parties (CoP 26) in Glasgow in 2021 to reach net-zero emissions by 2060 [11]. One of the commitments to these targets is a GHG emissions reduction program for the power generation sector, intending to achieve net-zero emissions by 2060. In Indonesia's Enhanced Nationally Determined Contribution (ENDC) document, there is a commitment to reduce Indonesia's GHG emissions by 31.89% against the baseline, or 915 million tons of CO_2e, through domestic efforts by 2030 and by 43.20%, or 1,240 million tons of CO_2e, with international support [12]. Short-term programs are outlined in the Electricity Supply Business Plan (RUPTL), updated annually. The 2021–2030 RUPTL is called the green RUPTL, progressively increasing the share of renewable energy sources, with new renewable power generation accounting for 51.6% by 2030 [13].

Electricity supply in the future is expected to continue increasing in line with the growth in electricity demand. According to National Energy Council (DEN) report [14], electricity demand is projected to reach 433 TWh (BAU scenario) and 702 TWh (OPT scenario) by 2032. The largest electricity consumer is the industrial sector, 46% in the OPT scenario, followed by the transportation and household sectors, each at 20%. This increasing electricity demand calls for an annual increase in power generation capacity of 4.6% (BAU) and 8.2% (OPT). As of 2022, coal power plants dominate power generation in Indonesia. The total coal power plant installed capacity stands at 42.1 GW, equivalent to 51.85% of Indonesia's total installed capacity [15,16].

The largest electricity supply comes from state electricity company (PT PLN Persero), followed by independent power producers (IPP), operating permits (IO), and private power utilities (PPU) [17]. The GHG emissions contribution from power generation reaches 40% of the total GHG emissions in the energy sector. Power generation is a significant source of sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other pollutants released into the atmosphere in substantial quantities [18], despite efforts to improve coal efficiency in mining, processing, and utilization [19]. DEN estimates that emissions will continue to rise until 2030 under BAU conditions, given the ongoing construction of several coal power plants [14]. According to RUPTL, coal power plant capacity will continue to grow until 2030, reaching 13.8 GW, with 3.3 GW from mouth-mine coal power plants and 10.5 GW from non-mouth-mine coal power plants [17].

Various low-carbon power plant technology options can replace coal power plants, including photovoltaic (PV) power plants and wind power plants integrated with battery energy storage systems (BESS), geothermal power plants, and hydropower plants [20]. Moreover, Indonesia has various renewable energy potentials in the form of hydropower from run-off rivers [21], hydro reservoir hybrids with floating solar PV [22], rooftop solar PV [23], and wind power [24]. However, the selection of each option needs to consider various factors such as resource availability, the condition of the electricity system, and GHG emissions reduction targets. Replacing base-load coal power plants with PV power plants requires the inclusion of BESS [25].

Several countries have been pursuing the substitution of coal power plants with renewable energy sources. Various studies have been conducted for selected countries, including China [19], Portugal [18], Germany [26–28], Japan [29], and Vietnam [30]. China has undertaken several steps to reduce the use of coal in power generation. These stages include refraining from constructing new coal power plants, phasing out the operation of existing coal power plants within 10–15 years, and replacing them using renewable energy systems integrated with BESS. Additionally, efforts involve decreasing coal usage through biomass co-firing and implementing carbon capture, utilization, and storage (CCUS) technologies. The adoption of CCUS necessitates significant investments, while BESS implementation requires a robust electricity grid system capable of supporting substantial renewable energy penetration [19]. Research in Portugal is focused on substituting coal power plants with PV power plants integrated with BESS to enhance renewable energy penetration. The proposed high penetration of PV power plant use will be achieved before 2025 because the cost of PV plant technology is already competitive and the condition of the electricity grid system in Portugal is already well-established [18].

Germany has proposed the cessation of coal usage by 2038, as coal power plants are major contributors to GHG emissions. The increased adoption of renewable energy in Germany, coupled with the reduction of fossil energy consumption, will enhance supply security. This can be understood because fossil energy is partially imported, while renewable energy technologies are already available [26]. Nevertheless, the elimination of coal power plants faces limited political support due to potential increases in social costs [27]. In contrast, the Japanese government continues efforts to maintain coal power plants by employing high-efficiency technologies. Simultaneously, the government has formulated policies and undertaken institutional reforms to promote renewable energy growth and reduce reliance on coal usage [29]. Vietnam has also set a target to phase out coal power plants by 2040 or earlier. This ambition stems from international support for sustainable growth initiatives and the limited financing options available for new coal power plant projects [30]. Research with case studies in Indonesia has also been conducted, Sunarko et al., study [31], which targets 100% renewable power generation by 2050 with the option of phasing out coal power plants and reducing GHG emissions by over 700 million tons of CO_2. According to the IESR report [20], the phase-out of coal power plants will be accelerated in 2040 under the Paris Agreement's 1.5 °C target.

The phase-out process of coal power plants can commence with a repurposing process, which involves redirecting their functions for more environmentally friendly purposes. Research by Jindal and Shrimali [32] discusses repurposing coal power plants in developing countries such as South Africa, Chile, and India. This process assesses the potential to reduce decommissioning costs, avoid specific environmental remediation requirements, and explore the possibility of reutilizing existing assets, such as generators and substations. Maamoun developed a retirement index that considers the age and capacity of coal power plants, annual CO_2 emissions, and the population exposed to air pollution emissions to determine the sequence of coal power plants to be retired [33].

The Indonesian government has plans to phase out coal-fired power plants [31,34]. One alternative to replacing coal power plants is using integrated PV plants with BESS. This plan faces challenges in terms of technical, economic, social, and environmental aspects. In this paper, we specifically address the economic perspective, focusing on the financial costs and benefits for power plant investors. Challenges related to technical and social aspects are not discussed here, while the environmental aspect only considers CO_2 emissions as an indicator of the energy transition process. The analysis results are expected to provide an understanding of the implications of planned energy transition policies and the crucial parameters to consider when implementing the phasing-out program.

2. Methods

Nowadays, there is not only the cost-benefit analysis (CBA) method for analyzing energy policy, but there are also other methods [34] such as multi-criteria evaluation [35], risk assessment [36]. There are no dominant evaluation methods because each method has strengths and weaknesses. Energy policy consequences have frequently been evaluated using CBA, involving the summation of the costs and benefits of each policy alternative over a specified period. Cash flow discounting techniques estimate costs and benefits in present value terms. A discount rate of 10% is assumed, which is commonly used in developing countries [37]. Various policy alternatives can be analyzed by identifying the net benefits in present value terms [38,39].

2.1. Assumptions and scenarios

The phasing-out of coal power plants is analyzed by comparing the base and phase-out scenarios. Both scenarios will be the basis for comparing the differences between the continued operation and the phasing-out of coal power plants. The calculations will involve projections of investment costs, operational and maintenance costs, fuel costs, revenue, and CO_2 emissions.

- The base scenario is analyzed based on the assumption that coal power plants will continue to operate for the long term. New coal power plants are needed to meet the long-term increase in electricity demand.
- The phase-out scenario will involve terminating coal power plant operations before their economic lifespan. Cost, benefit, and CO_2 emissions calculations will involve the construction of PV power plants integrated with BESS, and it is assumed that the decommissioning costs of coal power plants are relatively low and are not considered in this paper.

2.2. Cost and benefit components

The cost and benefit components considered for the analysis are those related to the economic aspects of power generation. In contrast, components related to the environment and society are not considered. Cost components include investment, operational, maintenance, and fuel costs. Investment costs encompass expenses related to the construction and development of power plants, such as planning costs, construction costs, and equipment procurement costs. Operational and maintenance costs encompass equipment maintenance and upkeep costs, labor costs, administrative expenses, and other costs related to power plant operations. Fuel costs, especially fossil-based power plants, are the most significant in power plant operations. These costs include fuel procurement, delivery, and storage expenses. The total cost in USD in year t is expressed in the form of net present value (NPV), which includes capital cost, fixed operation and maintenance cost (fixed O&M cost), variable operation and maintenance cost (variable O&M cost), and fuel cost. The formula for total cost is illustrated in Eq 1.

$$Total\ Cost_t = \frac{1}{(1+d)^t}\sum_p[annualized\ capital\ cost_{p,t} + fixed\ O\&M\ cost_{p,t} + variable\ O\&M\ cost_{p,t} + fuel\ cost_{p,t}] \quad (1)$$

where t is the year, and p is the type of power plant or BESS, and the discount rate (d) is 10%.

The benefit component represents the revenue that the power plant investors can obtain. Revenue can be calculated based on electricity generation multiplied by the government's tariff set. In this calculation, the base currency is USD; therefore, the current electricity tariff of 1,137.3 Rp./kWh is divided by the exchange rate of 15,731 Rp./USD. Based on MEMR [15] historical data from 2014 to 2022, an electricity tariff escalation factor of 2.4% per year is added from 2023 to 2060. Moreover, the total benefit in USD is calculated using Eq 2.

$$Total\ Benefit_t = \frac{1}{(1+d)^t}\sum_p[electricity\ generation_{p,t} * electricity\ tariff_t * escalation\ factor_t / exchange\ rate_t] \quad (2)$$

The CO_2 emissions are calculated based on fuel consumption multiplied by emission factors for each fuel type, derived from the Intergovernmental Panel on Climate Change (IPCC) database. The CO_2 emissions for each power plant (CE) are calculated using Eq 3.

$$CE_t = \sum_p[FC_{p,j,t} * EF_{j,t}] \quad (3)$$

Where FC representing the fuel consumption for power plant p and fuel type j in year t, and EF being the CO_2 emission factor for fuel type j in year t. For renewable energy-based PV and BESS power plants that do not require fuel, CO_2 emissions are considered zero.

The installed capacity of coal power plants in Indonesia in 2021 will reach 32.71 GW. The largest supply came from PT PLN Persero with an installed capacity of 15.21 GW, followed by IPP with 14.37 GW, and the rest from PPU and IO at 2.00 GW and 1.13 GW, respectively. The distribution of the installed capacity of coal power plants in each region is fully detailed in Table 1.

Table 1. Installed capacity of coal power plants in Indonesia (2021). Source: Calculate from Ditjen Gatrik [16].

No.	Region	Coal P.P. (GW)				Total (GW)
		PLN	Non-PLN			
			IO	IPP	PPU	
1	Aceh	0.22	–	–	–	0.22
2	North Sumatra	1.09	0.01	–	–	1.10
3	West Sumatera	0.22	0.01	–	–	0.23
4	Riau	0.24	0.13	–	–	0.36
5	Riau Islands	0.02	–	–	0.13	0.15
6	Bengkulu	–	–	0.23	–	0.23

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No.	Region	Coal P.P. (GW)				Total (GW)
		PLN	Non-PLN			
			IO	IPP	PPU	
7	Jambi	–	0.01	0.01	0.00	0.02
8	South Sumatra	–	–	–	–	0.00
9	Bangka Belitung Islands	0.09	0.03	–	–	0.12
10	Lampung	0.40	0.05	0.01	0.00	0.47
11	Banten	5.57	–	2.71	0.30	8.58
12	Jakarta	–	–	–	–	0.00
13	West Java	2.04	–	0.66	0.31	3.01
14	Central Jawa	1.29	–	5.02	–	6.31
15	Yogyakarta	–	–	–	–	0.00
16	East Java	2.79	0.21	3.27	–	6.27
17	Bali	–	–	0.43	–	0.43
18	West Kalimantan	0.17	–	0.27	–	0.44
19	Central Kalimantan	0.13	0.01	0.25	–	0.38
20	South Kalimantan	–	0.06	–	0.05	0.11
21	East Kalimantan	0.24	0.06	0.46	0.08	0.83
22	North Kalimantan	0.01	0.01	–	0.01	0.02
23	North Sulawesi	0.11	–	0.18	–	0.29
24	Gorontalo	0.06	–	0.08	–	0.14
25	Central Sulawesi	0.01	0.01	0.06	1.13	1.21
26	West Sulawesi	–	–	0.06	–	0.06
27	South Sulawesi	0.31	0.12	0.46	–	0.89
28	Southeast Sulawesi	0.03	0.06	0.14	–	0.23
29	West Nusa Tenggara	0.10	0.16	0.05	–	0.31
30	East Nusa Tenggara	0.05	–	0.03	–	0.08
31	Maluku	–	–	–	–	0.00
32	North Maluku	0.01	0.00	–	–	0.01
33	Papua	0.02	0.20	–	–	0.22
34	West Papua	–	0.01	–	–	0.01
Indonesia		15.21	1.13	14.37	2.00	32.71

3. Results

Coal is currently a crucial source of electricity generation. The use of coal, which has the lowest electricity production costs from the consumer's perspective, makes coal power plants an affordable electricity supply. The phase-out of coal power plants, of course, requires a source of funding to construct renewable energy-based power generation as replacements.

3.1. Projections for electricity generation and installed capacity

Sugiyono et al. [40] has conducted long-term (2019–2050) projections of power plant electricity generation and installed capacity. These projections will be used as the base scenario, extending to 2060.

For 2051–2060, electricity generation growth is assumed to follow previous trends. Historical data and projections for electricity generation and the installed capacity of power plants from 2019 to 2050 are shown in Figure 1. The electricity demand is expected to increase from 232 TWh in 2022 to 1,574 TWh in 2060. This growth in electricity demand will be accompanied by an increase in generation capacity, from 78 GW in 2022 to 361 GW in 2060, with an average annual growth rate of 4.1%. The role of coal power plants will remain dominant when generation planning is based on the least cost.

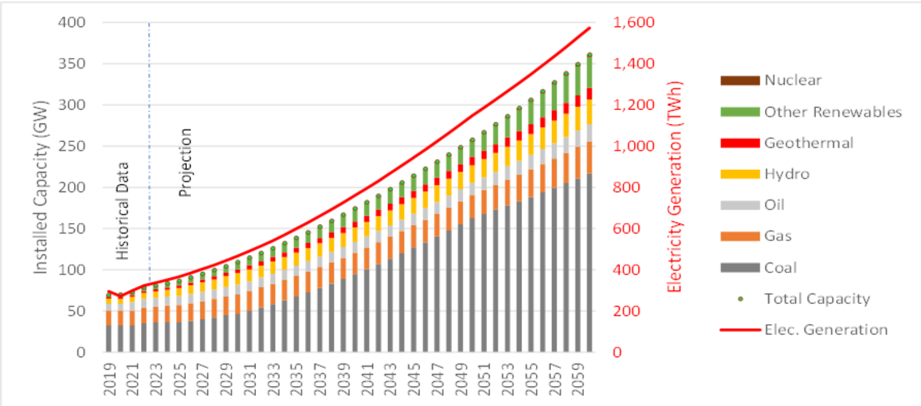

Figure 1. Projections for the generation and installed capacity of power plants.

Coal power plants are typically used to supply base-load power means a stable and continuous electricity supply throughout the day. Replacing them with PV power plants requires an integration strategy with BESS to ensure a non-intermittent electricity supply. PV power plants are vulnerable to weather changes, such as cloudy conditions. On average, it is assumed that a PV power plant can operate and generate electricity for 6 hours per day, requiring an installed capacity four times that of a coal power plant to replace it. Moreover, the BESS used to store some of the electricity from the PV power plant has a capacity of three times that of the coal power plant. A schematic representation of the replacement of coal power plants with PV power plants integrated with BESS is shown in Figure 2.

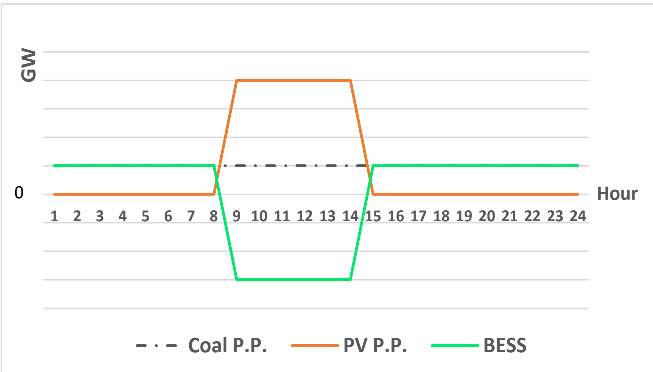

Figure 2. Equality of coal power plant capacity with PV power plants integrated with BESS.

The government has been discussing plans for phasing out coal power plants as part of efforts towards a cleaner and more sustainable energy transition. This plan is in the finalization process, and there has yet to be an official decision regarding the phasing out of coal power plants. Kusdiana [41] provides an overview of the stages of coal power plants that will be phased out. The gradual phase-out of coal power plants is illustrated in Figure 3. In the base scenario, the coal power plant capacity increases from 38 GW in 2022 to 217 GW in 2060. In the phase-out scenario, the coal power plant capacity will peak at 45 GW in 2030. Over the long term, the coal power plant capacity will gradually decrease to zero by 2058. This implies the addition of new power plant capacity, initially based on coal power plants, to be replaced by PV power plants integrated with BESS.

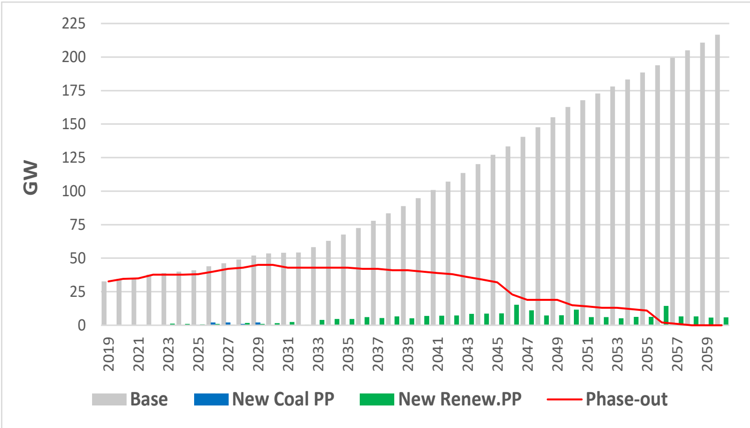

Figure 3. Projected installed capacity of coal power plants (base and phase-out scenario).

Based on the projected total installed capacity of coal power plants for the period up to 2060, the addition of new power plant capacity can be calculated by considering electricity demand and the economic lifespan of power plants. The addition of installed capacity for new power plants, both coal power plants (base scenario) and PV power plants integrated with BESS (phase-out scenario), is shown in Figure 4. After 2030, a significant increase in capacity addition will be required for the phase-out scenario, reaching over 10 GW per year, and peaking in 2046 at 60 GW for PV power plants and 45 GW for BESS. This capacity addition must be further considered as it will require a substantial investment.

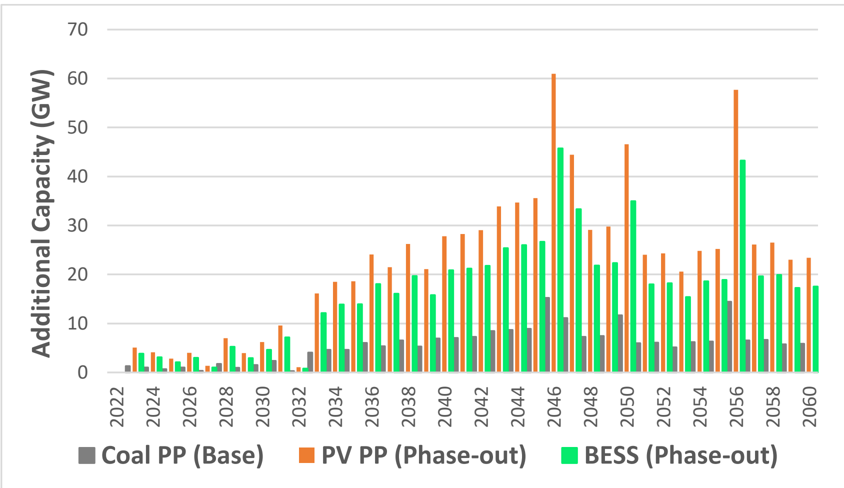

Figure 4. Additional capacity of power plant annually.

3.2. Cost-benefit analysis

The cost and benefit are calculated based on the capacity addition projections' results and secondary data obtained from various publications. The technical and economic data for calculations are shown in Table 2. The coal price is based on the domestic market obligation (DMO) price, which is 70 USD/ton [42].

Table 2. Technical and economic data on coal and PV power plants and BESS. Source: calculated from [43–45].

Parameters	Unit	Coal power plant			PV power plant			BESS		
		2020	2030	2050	2020	2030	2050	2020	2030	2050
Investment cost	USD/kW	1,650	1,600	1,550	790	560	410			
Energy component	USD/kWh							152	62	35
Power component	USD/kW							311	184	69
Others component	USD/kWh							115	110	105
Fixed O&M cost	USD/MW/yr	45,300	43,900	42,600	14,400	10,000	8,000			
	USD/MWh/yr							621	311	155
Variable O&M cost	USD/MWh	0.13	0.13	0.12				2.3	2.07	1.84
Capacity factor	%				19	22	22			
Lifetime	year	30	30	30	30	40	40	20	25	30
Efficiency (net)	%	34	35	36						

The phasing out of coal power plants is expected to provide economic and environmental benefits. The calculations of present value, cost, and benefit are shown in Figure 5. The present value of costs for the base scenario from 2023–2036 is relatively lower compared to the phase-out scenario. However, in the long term, the costs of the phase-out scenario will gradually decrease and become more affordable. The costs for the phase-out scenario from 2023–2030 are higher than the benefits, but after 2031, the costs decrease as investment costs decline, both for PV power plants and BESS. The total benefit-cost ratio for the 2023–2030 phase-out scenario is 2.36, while the base scenario is 2.12, indicating that the phase-out scenario is more prospective for future development. Appropriate PV and PV-BESS systems are arranged to determine the price structure that is advantageous to both owners and the utility and expedite the shift to more efficient utilization of renewable resources [45].

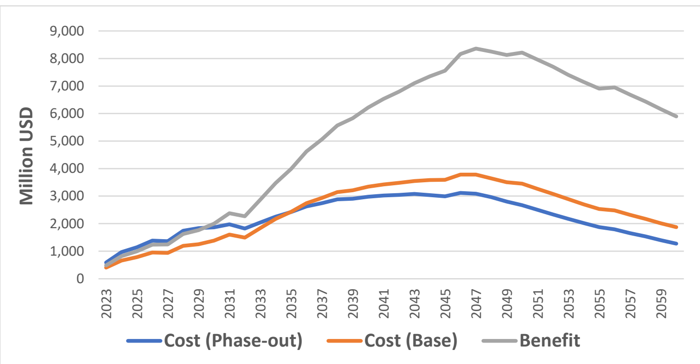

Figure 5. Present value cost and benefit for the base and phase-out scenario.

The coal price is a critical factor to consider in the long term. With the DMO price, the costs of coal power plants appear to be cheaper than the benefits. However, if the coal price is based on the current market price of 276.58 USD/ton [6], then coal power plants are not prospective for development. Several donor countries have also stopped financing new coal power plant construction [46].

3.3. CO_2 emission

The base scenario will result in continuously increasing CO_2 emissions with an average growth rate of 4.1% annually from 2022 to 2060. In 2022, CO_2 emissions were 229.8 million tons of CO_2, and they will reach 1,039.4 million tons of CO_2 in 2060 (see Figure 6). In the phase-out scenario, CO_2 emissions will gradually decrease and reach net zero by 2056. These CO_2 emissions are correlated with electricity generation from coal power plants, whereas if replaced with PV power plants integrated with BESS, they do not produce CO_2 emissions.

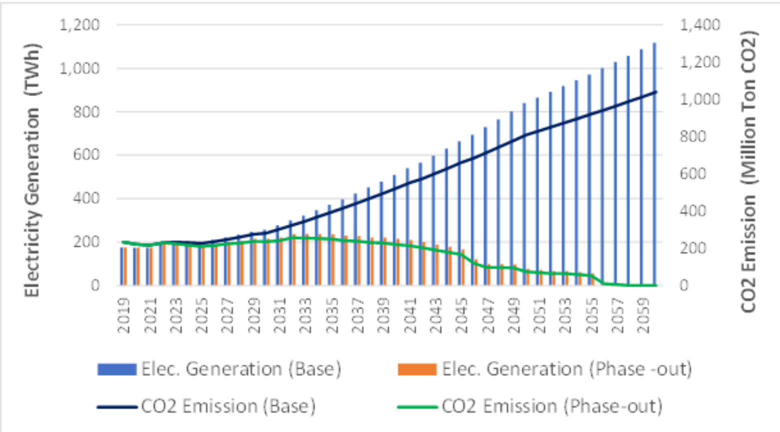

Figure 6. Electricity generation from coal power plants and CO_2 emissions (base and phase-out scenario).

4. Discussion

The energy transition strategy must consider various factors, especially Indonesia as an archipelagic island with varying regional conditions. The lessons learned in evaluating the coal power plant phase-out process can be traced to several previous studies, such as those for Germany [47], China [48], and India [49]. It is crucial for the government to manage the impacts of the phase-out process to ensure a sustainable and equitable transition process [50]. The cost-benefit analysis shows that for the base scenario, power plant investors will gain a net present value profit of 104.5 billion USD over the period from 2023 to 2060, and CO_2 emissions will increase. In contrast, for the phase-out scenario, investors will gain a profit of 114.2 billion USD, and simultaneously, CO_2 emissions reduction will achieve net zero emissions in the long term, in line with the government target. Based on the cost-benefit analysis and GHG emissions considerations, the government can focus more on developing the phase-out scenario and conducting more detailed studies.

Quantifying environmental factors such as CO_2 reduction and emissions of other pollutants into cost-benefit analyses is crucial. Various methods are used to quantify environmental factors, such as life cycle cost analysis and external cost calculations. Huang et al. [51] utilized life cycle cost analysis to compare environmental costs between coal power plant and PV power plant usage, while Rokhmawati et al. [52] calculated the external costs of coal power plants in Indonesia. The government is currently moving towards quantifying these environmental factors. The economic value of carbon policies aimed at internalizing carbon costs in economic decision-making has been issued in Presidential Regulation No. 98/2021, specifically for power generation in Ministerial Regulation No. 16/2022. Carbon trading mechanism regulations have also been introduced to promote low-carbon, green economic activities. However, these mechanisms are in the trial phase and have yet to be widely implemented.

5. Conclusions

The contribution of GHG emissions from power plants in Indonesia accounts for 40% of the total GHG emissions in the energy sector. Coal power plants constitute the primary source of these emissions. The government is giving serious attention to reducing GHG emissions from power plants in line with the energy transition program. One of the initiatives involves replacing coal power plants with PV power plants integrated with BESS. The prospects of this program are evaluated through a cost-benefit analysis from the perspective of power plant investors.

The option of phasing-out coal power plants and replacing them with PV power plants integrated with BESS in the long term holds promising prospects. The phase-out scenario has a total net present value benefit from 2023 to 2060 of 114.2 billion USD and a benefit-cost ratio of 2.36, which is higher than the base scenario with values of 104.5 billion USD and a benefit-cost ratio of 2.12, respectively. Furthermore, the phase-out scenario has an advantage over the base scenario in achieving the net zero emissions target by 2056. Although power plant investments appear promising from an investor's standpoint, the Indonesian government needs to promote gradual phases of coal power plant phase-out. Presently, the government has already reduced GHG emissions by implementing biomass co-firing for coal power plants and refraining from constructing new coal power plants. This aligns with commitments in the ENDC and international pressures related to limited financing options for new coal power plant projects. Technically, the government, through PT PLN Persero, needs to establish an electricity grid system capable of supporting significant renewable energy penetration to facilitate the coal power plant phase-out. Additionally, policy support and incentives are required to address the increasing capital costs associated with the development of PV-power plants integrated with BESS.

Further research can be conducted with more detailed cost-benefit analysis calculations that include decommissioning costs, which encompass closure expenses, land reclamation, asset removal, and their impact on labor and surrounding communities. Evaluations related to coal price projections and long-term electricity tariffs are also crucial to assessing the sustainability of power generation development over the long term.

Use of AI tools declaration

The authors declare that the research conducted and presented in this article has not used AI tools at all stages of the research process.

Conflict of interest

The authors declare that there are no conflicts of interest in the writing and publication of this work.

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