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Reducing Fossil Fuel Dependence and Exploring Just Energy Transition Pathways in Indonesia using OSeMOSYS (Open-Source Energy Modelling System)

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Abstract: Indonesia's commitment to the Paris Agreement and its Nationally Determined Contribution (NDC) is not adequately reflected in the significant CO_2 emissions from fossil fuel-intensive energy sector, albeit enormous potential of renewable energy sources in the country. The ongoing coal regime, which has been a major contributor to Indonesia's economy and employment sector, has led to electricity oversupply and air pollution problems. Although it poses a huge challenge for Indonesia, a just energy transition away from fossil fuel is crucial. This study aims to explore the ideal energy mix and key emissions reduction pathway in Indonesia in achieving a just energy transition using a least-cost optimisation energy modelling tool OSeMOSYS.
Six scenarios are modelled over 2015-2050 including coal phase-out, NDC, Just Energy Transition Partnership (JETP), and carbon tax implementation. The result highlights that solar, geothermal, and hydropower are the alternatives for coal decommissioning. Despite the large-scale investment in renewable energy under the NDC and JETP scenarios, emissions could be reduced by 55% and 52%, respectively, by 2050. Moreover, Indonesia's current carbon tax rate won't lead to a significant emission reduction. Three recommended policies include (1) Accelerate CFPP retirement; (2) Impose an aggressive carbon tax rate; (3) Prioritise investment on solar technologies.

Keywords: OSeMOSYS; Just energy transition; Energy modelling; Renewable energy; Indonesia

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1. Introduction

1.1. Overview

Indonesia, the world's fourth-most populous country, experiences continuous population growth [1], contributing to a rapid annual increase in overall energy and electricity demand, projected at around 4.9% [2]. However, the International Energy Agency (IEA) suggests an overestimation of demand and oversupply of Coal-Fired Power Plants (CFPP) [3], creating financial pressure on both the state-owned company (PLN) and government expenditures [4]. This surplus stems from inconsistent energy balance, with the supply constantly surpassing consumption by 18.2% over the last five years [5]. Intensified with the initiation of 35GW CFPP national megaproject in 2015, the construction of new CFPPs has led to electricity generation and consumption imbalances in Indonesia. In 2021, coal contributed to 66% of Indonesia's electricity generation mix, as shown on Figure 1. Therefore, electricity oversupply is one of the energy challenges in the country.

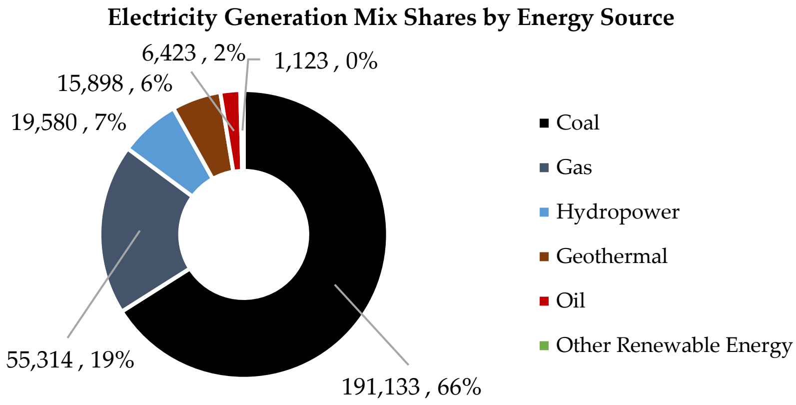


Figure 1. Electricity Generation Mix Shares by Energy Source, 2021 (GWh, %). [6]

Abundant coal and oil reserves have historically made fossil fuels the primary energy source in Indonesia [5], as illustrated on Figure 2. Despite being the world's largest oil exporter until 2003 [7], production declined in the following years, turning Indonesia into a net importer [8]. In response, the current energy strategy aims to reduce reliance on imported oil and promote local resources for economic growth, resulting in increased coal mining [9]. In 2021, coal, oil, and gas accounted for 38%, 33%, and 17% of the primary energy mix, respectively, while renewable energy contributed to only 12% [5].

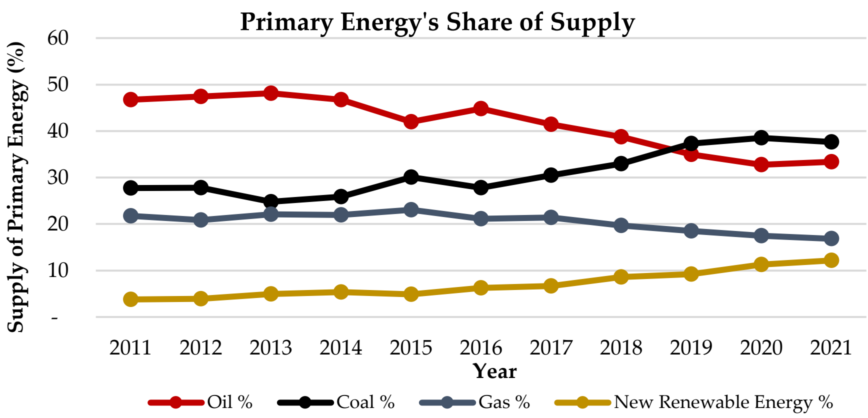


Figure 2. Share of Supply of Primary Energy, 2011-2021 (%). [5]

Indonesia, ranked among the top greenhouse gas (GHG) emitters globally, contributes to 1,050,412 GgCO_{2}e emissions in 2020 [10]. Energy sector, which also includes the power sector, contributes to 56% of the country's emissions and becomes the highest emitting sector by 2020 [10], thus playing a significant role in decarbonisation. Beyond environmental consequences, GHG emissions significantly impact public health, including respiratory issues and heat-related diseases [11]. With the estimated health cost at US$15.98/MWh and a total of 120 CFPPs in Indonesia, the impact for the generation is intolerable [12]. Exacerbated by the fact that Jakarta, the capital, was the world's most polluted city, largely due to the emissions from nearby CFPPs [13], air pollution ranks among the top five leading causes of mortality in Indonesia with an annual toll of 123,000 deaths [14]. This highlights the urgent need for a transition to cleaner energy.

1.2. Literature Review

Several studies have previously evaluated Indonesia's power system through the lens of least-cost modelling analyses. Sarjiya et al [15] examined the generation expansion of the main power grid in Indonesia, Jawa-Bali power system, using OSeMOSYS. Gupta [16] analysed fuel-switching and energy efficiency measures in the residential, commercial, and transportation sector using OSeMOSYS. Reyseliani and Purwanto [17] investigated modelling approaches across all power grids in achieving 100% renewable energy using another modelling tool, VEDA TIMES. Paiboonsin et al [18] modelled six clean energy transition scenarios including net zero 2050 and 2060 using OSeMOSYS. However, the impact of Indonesia's pursuit of a just energy transition on its future power generation mix, CO_2 emissions, and capital investments remains to be thoroughly explored.

The shift in energy structures involves changes in technology, institutions, employment, and socio-economic aspects at all levels. A just energy transition prioritises individuals and communities [19], addresses justice concerns for those affected, and fosters equality in society and job opportunities [20]. Moreover, a just transition mechanism encourages economic diversification [21] and minimises socio-economic shocks from ambitious energy transition commitments [22].

Given the substantial investment required for a just energy transition, financially capable nations may navigate it more easily than emerging countries [22]. Hence, international support, particularly through initiatives like the Just Energy Transition Partnership (JETP) is crucial [23]. The Indonesian JETP involves US$20 billion investment from an international partner group, and serves as a financing model, focusing on the social impact of transitioning away from coal [24]. However, there are barriers from multi-dimensional factors in realising a just energy transition in Indonesia.

First and foremost, many academics, NGOs, businesses, and other stakeholders have proposed that the primary challenges in implementing a just energy transition in Indonesia are associated with political and institutional issues [25, 26, 27]. These include a lack of national capacity to formulate relevant policies and provide skilled labour [20], inconsistent and unstable political landscape [26], also conflicts among decision makers at both vertical and horizontal levels [28]. Indonesia's stable regime of fossil-fuel based energy [28], the coal industry's strong connection with political stakeholders [9] along with politically-driven support of fossil energy, drive pressure to continue exploiting fossil energy sources [29] despite ongoing efforts for institutional reforms [26].

Secondly, political and institutional barriers have significantly impacted the economic and financial sectors in Indonesia's energy transition. Government allocates a limited budget for climate action, ranking it lower than other sectors [30], and views the decarbonisation framework, such as renewable energy development, as a significant burden [31]. Even, the private sector deemed it as a high-risk investment due to its substantial capital expenditure [32], thus unattractive to investors [9] and creating market inefficiency [33]. This is evident in the low investment in relevant projects [26]. With the addition of complex bureaucratic procedures associated with capital-intensive renewable energy projects [26], the interest rates increase to double-digit figures [9].

Thirdly, fossil fuel energy outperforms the renewable in terms of dispatchability, technical maturity, and cost-effectiveness [34]. Furthermore, there may be incompatibility between existing technologies and renewable energy specifications in the country [26]. Often involving imported power plant components [26], the Decree of Minister of Industry of Indonesia Number 5 of 2017 mandated that at least 60% of solar photovoltaic (PV) infrastructure components must be domestically sourced. This requirement, aimed at promoting local production, poses a significant challenge to the expansion of solar PV in Indonesia due to resource limitations and industry readiness [35]. As a relatively new technology, renewable energy may also entail complex maintenance processes and technical operational inefficiencies and intermittencies, resulting in higher operational and maintenance costs [35]. Also, although Indonesia relies on power grids for transmitting and distributing electricity, 'take-or-pay' contracts between PLN and the independent power producer restrict the flexibility needed to effectively integrate renewables to the grid system [9].

Lastly, in addition to institutional unawareness, the local community confronts similar challenges. As most renewable energy sources are located outside urban areas, the local community expresses greater concerns about the immediate consequences of renewable energy projects than the future benefits [26]. This is intensified by the low rate of rural electrification, potentially requiring substantial subsidy support for the expansion of renewable energy deployment, a notion that is not commonly granted [22]. Additionally, transitioning from carbon-intensive fields to renewable energy, which demands advanced technical expertise, may lead to job losses, transfers, and expansions. This shift directly affects 165,000 coal miners and 1.2 million labourers in Indonesia's coal mining sector [36]. Exacerbated by the frequent job rotation within the related sector, impacting the workforce's skill and competency standards required for successful implementation of renewable energy projects [26].

Indonesia has implemented various energy sector regulations to reduce coal dependence, diversify energy sources, and meet the Paris Agreement. The National Electricity Supply Business Plan (RUPTL) of 2021-2030 limits new CFPP construction with the exception of ongoing projects and planning gradual CFPP retirement from 2030 [2]. Moreover, the Acceleration of Renewable Energy Development for Power Supply through the Presidential Decree Number 112 of 2022 mentioned the ban of new CFPP construction except for those stated in previous law and willing to minimise the emissions from the power plant. GHG emissions reduction targets are ratified through Enhanced NDC of 2022: 12.5% without international aid or 15.5% with international aid by 2030 [37].

A just energy transition framework enables a country to evaluate its energy policy and progress towards low-carbon goals in NDC commitments to the Paris Agreement [38]. Despite numerous studies on Indonesia's energy system, there is a notable gap in comprehensive research, particularly in energy system modelling that incorporates the latest ratified policies and targets such as Enhanced NDC and JETP. Therefore, this study aims to address this gap in modelling the energy mix and key pathways for emissions reduction in Indonesia by analysing potential scenarios for the energy mix considering environmental, economic, and technical factors. The objectives include analysing several potential scenarios of different policy and investment constraints, examining optimal energy mix, and identifying feasible policy recommendations.

2. Methodology

2.1. OSeMOSYS as a Modelling Approach

The model of Indonesia's electricity system is developed using OSeMOSYS (Open-Source Energy Modelling System), an energy system optimisation for planning and decision-making by generating least-cost and locally-focused alternatives for energy sources [39]. This is particularly crucial for Indonesia, given its financial constraints in transitioning to cleaner energy sources.

Using a bottom-up approach, OSeMOSYS focuses on the detailed structure of the energy system, and provides insights into the cost, performance, and environmental impacts of various technologies [40]. Its goal is to determine the most optimal and least-cost solutions by aligning with the intended demand, policy objectives, system constraints, and country-specific technoeconomic data. Moreover, OSeMOSYS addresses cost minimisation related to capital investments, operating expenses, emissions penalties, and salvage value variables [41]. It also allows the flexibility of new scenarios and hypotheses analysis in medium to long-term through the simplification of complex energy modelling [43]. In compliance with the U4RIA concept (Ubuntu, Retrievability, Repeatability, Reconstructability, Interoperability, Auditability) [42], OSeMOSYS provides a user-friendly and accessible spreadsheet-based interface, in which this study utilises clicSAND (Simple and Nearly Done) 3.0 interface.

The general assumptions used in this study include a discount rate of 4.78% based on Indonesia's Central Bank rate [44], modelling period from 2015 to 2050, and time variability assumption of 4 time-slices representing 2 seasonal conditions in Indonesia as an equatorial country – dry season (April to October) and wet season (November to March) and 2 daily load profile – day (06AM to 06PM) and night (06PM to 06AM).

2.2. Reference Energy System

Indonesia's energy system is defined through a simplified diagram that includes 14 commodities (primary resources for power generators), 9 technologies (existing power generators in Indonesia), and final electricity demand, illustrated in Figure 3. The resources also encompass imported commodities for electricity generation, such as coal, light fuel oil, heavy fuel oil, natural gas, and biomass.

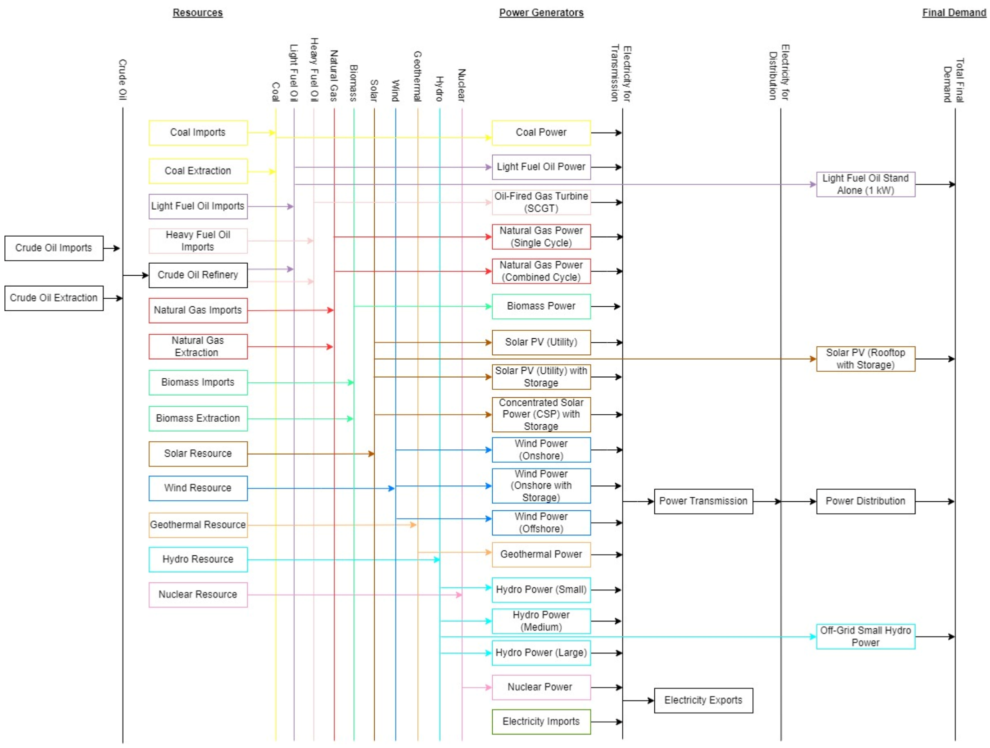


Figure 3. Reference Energy System of Indonesia.

2.3. Demand Projection

Electricity demand of Indonesia's energy system in this study is specified from three categories, industrial, residential, and commercial; with the total demand is listed on Table 1. The electricity demand data is sourced from Paiboonsin (2023) [57].

Table 1. Total Electricity Demand Between 2015 and 2050, With 5 Years Interval (PJ). [57]

Demand	2015	2020	2025	2030	2035	2040	2045	2050
Electricity Demand	777.91	1,005.42	1,206.80	1,525.29	2,000.87	2,484.82	2,952.49	3,329.43

2.4. Techno-economic Input Data

The main techno-economic data in this study involves cost (capital, fixed, variable), efficiency, installed capacity, electricity production, and the operational lifetime of each power plant. While the cost data is available in 10 and 20-years intervals (2020, 2030, and 2050), Table 2 listed the data of 2020. Furthermore, the data of coal and geothermal technology in this study is the average value of the existing types in Indonesia (coal – subcritical, supercritical, ultra-supercritical power plant ; geothermal – small and large power plant).

Variable cost in this study reflects the fuel cost of each technology, thus it is assumed that some renewable energy technologies have 0 variable cost. The costs and operational lifetime data is sourced from Ministry of Energy and Mineral Resources (MEMR)'s Technology Data for the Indonesian Power Sector publication [45]. Most capital cost, except for geothermal, includes the engineering, procurement, and construction cost. The learning rates for each technology vary between 10-15% which also yield the cost reduction in later years [45]. Meanwhile, the efficiency data for the power plant is obtained from Paiboonsin (2023) [57, 58].

Table 2. Techno-economic Data of Technologies in Indonesia (2020). [45, 57]

Technology	Capital Cost (USD/kW)	Fixed Cost (USD/kW/year)	Variable Cost (USD/kWh)	Efficiency (%)	Lifetime (Years)
Coal	1,530	47.7	2.49	30	30
CCGT	690	23.5	2.62	55	25
SCGT	770	23.2	2.62	34	25
Biomass	2,000	47.6	0	38	25
Geothermal	4,500	57.5	0	N/A	30
Diesel	800	8	6.62	40	25
Utility-scale Solar PV	790	14.4	0	N/A	35
Large Hydropower	2,080	37.7	0	N/A	50
Medium Hydropower	2,290	41.9	0	N/A	50
Small Hydropower	2,700	53	0	N/A	50
Onshore Wind	1,500	60	0	N/A	27
Offshore Wind	1,300	72.6	0	N/A	27
Nuclear Power	5,500	138	0	33	60
Utility-scale PV with 2-hour Storage	1,869	18.69	0	N/A	30
Onshore Wind with Storage	2,466	98.65	0	N/A	30
Diesel with Standalone Generator (1kW)	1,500	38	6.62	42	20
Solar PV (Distributed with Storage)	2,130	42.62	0	N/A	41
Off-grid Hydropower	2,162	64.86	0	N/A	40

2.5. Renewable Energy Potential

As an archipelagic and equatorial country, Indonesia has an abundant renewable energy resources potential, such as geothermal, hydropower, wind, and specifically solar energy with constant year-round availability [46]. However, the development and its realised power plant capacity as of 2022 is relatively low, only 0.3% [47].

Table 3. Total Renewable Energy Potential and Realisation [47]

Renewable Energy	Potential (GW)	Realisation (GW)
Geothermal	23.9	2.3
Bioenergy	56.9	2.3
Wind	154.9	0.2
Hydropower	95	6.6
Solar	3,294	0.2

2.6. Scenario Definition

In this study, seven scenarios are modelled to investigate the impacts of the baseline, phasing out CFPP, levying carbon tax, and implementing decarbonisation targets of NDC and JETP. Details of each scenario are described below.

- **Scenario 1: Baseline Least Cost (Least Cost)**
  Least Cost scenario is a baseline or business-as-usual model to be compared with other scenarios, to illustrate Indonesia's current energy landscape by assuming that the current regulatory framework is implemented until the end of the modelling period. In the model, there are no constraints on electricity generation from fossil-powered plants and no coal phase-out.
- **Scenario 2: Coal Phase-Out 2045**
  This scenario assumes that a phasing out of CFPP occurs in 2045. This scenario may depict alternative energy mix and emissions reduction pathways if the predominant yet unsustainable electricity generation source is phased out.

- **Scenario 3: Moderate Carbon Tax**
  This scenario uses the current carbon tax rate (US$1.98/t$CO_2$e) proposed by Government through Law Number 7 of 2021 to examine the emissions reduction and optional energy mix once this emissions penalty is effectively enforced in Indonesia.
- **Scenario 4: Aggressive Carbon Tax**
  This scenario uses a more aggressive carbon tax rate to analyse the effectiveness of current carbon tax rate in Indonesia by evaluating the emissions reduction gap from Scenario 3. This study uses Denmark's carbon tax rate (US$26.53/t$CO_2$e) as a benchmark given its success in achieving 23% emission reduction in the country between 2005 and 2018, surpassing the performance of other European countries [48].
- **Scenario 5: Unconditional NDC**
  This scenario represents Indonesia's Enhanced NDC target of 2022, which includes 12.5% emissions reduction by 2030 (justified from a 12.5% emissions reduction target in the energy sector, which involves the power sector) and energy mix share target by 2025 (minimum 23% renewable energy, maximum 25% oil, minimum 30% coal, minimum 22% gas) [37].
- **Scenario 6: Conditional NDC**
  This scenario is similar to Scenario 5 but achieving its objectives with international support and more ambitious targets, aiming for a 15.5% reduction in emissions by 2030 (justified from a 15.5% emissions reduction in the energy sector, which includes the power sector) [37].
- **Scenario 7: JETP**
  This scenario refers to JETP targets of 19% emissions reduction by 2030 (justified from 67MtCO_2 reduction from the baseline value of 357MtCO_2), 34% renewable energy share in the energy mix, and early retirement of CFPP (assumed in 2035, earlier than Scenario 2, yet aligned with the JETP plan of starting coal phase-out after 2035) [49].

3. Results

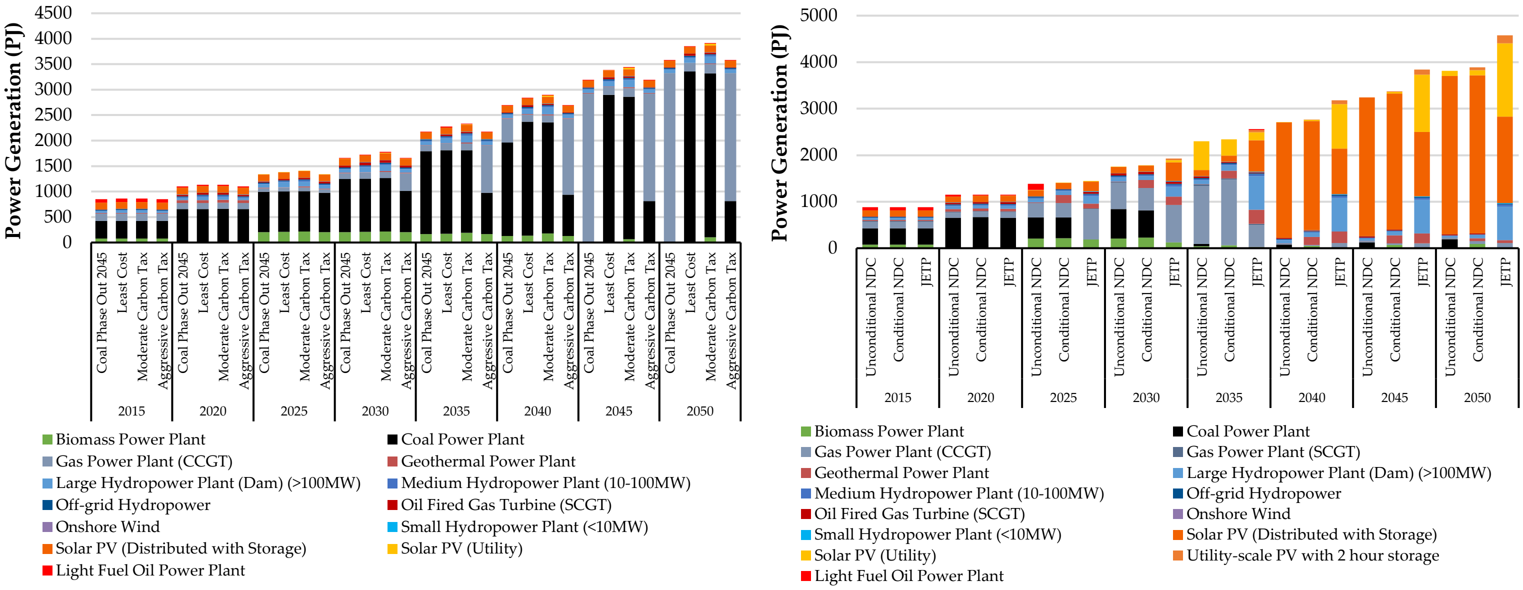
This section shows the scenario results of electricity generation, installed capacity, emissions, and cost. The figure for electricity generation and installed capacity is divided into two parts, detailing baseline least cost scenario in comparison to the independent emission reduction policies (coal phase-out and carbon tax) first and national decarbonisation targets (NDC and JETP) then.

3.1. Electricity Generation

In the business-as-usual and moderate carbon tax scenario, electricity generation increases to almost 4,000 PJ in 2050 and coal continues to be the predominant power source until the end of the modelling period. The variation in power generation across scenarios may be due to different constraints that affect decision of energy efficiency or end-use electrification. Meanwhile, natural gas replaces coal as the main fuel source from 2040 in the aggressive carbon tax scenario and from 2045 in the coal phase-out scenario. As the model investigates the least-cost alternative, it chooses a technology with the second lowest overall cost compared to the available fuel options, after coal, natural gas. However, those scenarios alone are not able to meet the NDC and JETP target of 23% renewable energy by 2025, as illustrated on Figure 4 (a).

In Figure 4 (b), it shows that the renewable energy mix target of NDC can be achieved by utilising 12% geothermal, 10% solar, and 7% hydro in the electricity mix in 2025, then reaching 30% renewable energy by 2030. On the other hand, the renewable energy mix target of 2030 in the JETP scenario can be realised through 21% solar, 12% hydropower, and 10% geothermal. Thus, it can be concluded that Indonesia may have to invest hugely in solar technology as the current realisation is only 0.01% compared to its potential [47].

In the absence of coal phase-out constraints, coal generation can only be constant until 2050 with the adoption of a more aggressive carbon tax rate. Consequently, the reduction of coal generation to as low as 5% in the electricity mix in 2050 can be achieved through the implementation of NDCs and JETP scenarios. In the JETP scenario, the renewable energy share on electricity mix increases from 34% in 2025 and 43% in 2030, to nearly 100% in 2050. The electricity generation diversifies to include geothermal, solar, hydropower, and under 1% of onshore wind technology (in 2030). In contrast, without intervention, coal technology is projected to expand and contribute to 88% of electricity mix by 2050, which aligns with the study by Reyseliani and Purwanto (2021) of a baseline scenario [17].



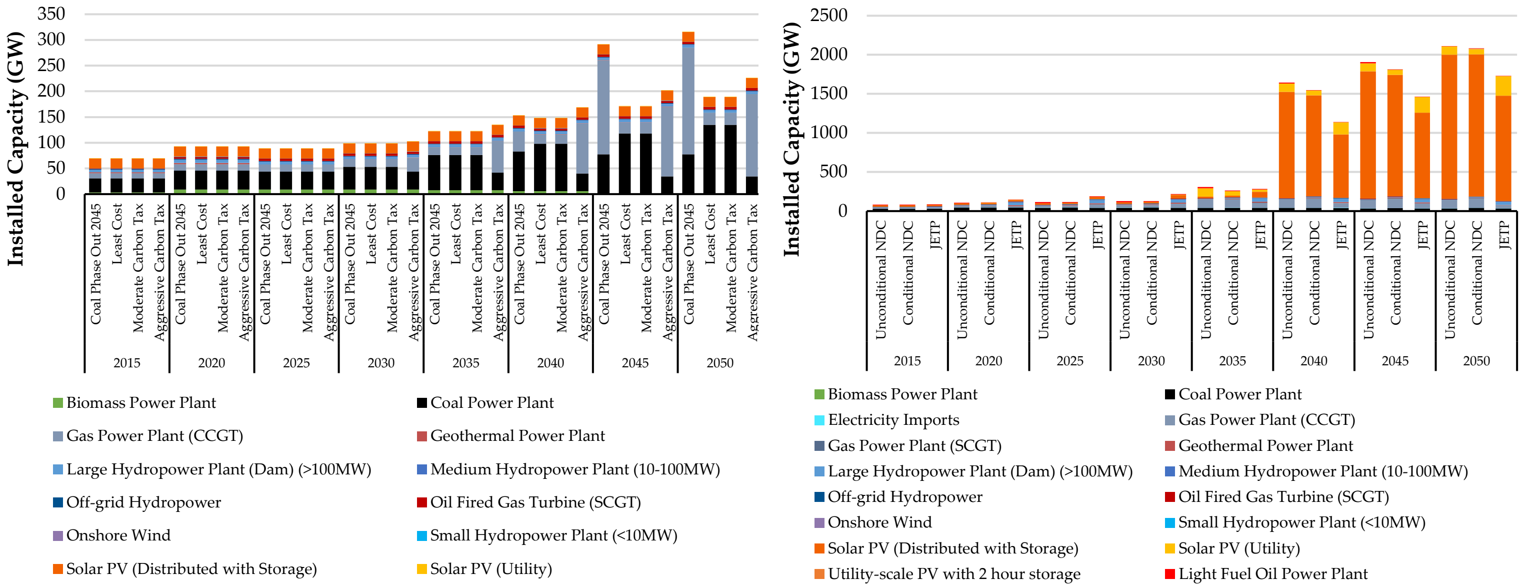
(a) **(b)**

Figure 4. Annual Electricity Generation, 2015-2050 (PJ). (**a**) Least Cost, Coal Phase Out, and Carbon Tax Scenarios; (**b**) NDCs and JETP scenarios.

3.2. Installed Capacity

Total power generation capacity increases across all scenarios, with the highest growth rate in Aggressive Carbon Tax and Coal Phase-Out scenario. This growth spans from 13GW in 2030 to 160GW in 2050, driven by limitations of electricity generation from coal plants in 2045 and as the alternative, a huge natural gas employment to meet the growing electricity demand. Yet, the highest coal capacity is evident in the Least Cost and Moderate Carbon Tax scenarios, peaking at 134GW in 2050.

Solar PV with storage capacity maintains a consistent value of 19GW throughout the modelling period in the Least Cost, Coal Phase Out, and Carbon Tax scenarios. In the NDC and JETP scenario, the model chooses solar technology as the alternative in achieving the targets when there is a constraint in electricity generation from CFPP. Thus, the capacity of solar increases significantly in 2040, dominating the electricity system and potentially serving as reserves for electricity generation. Solar technology's prioritisation is likely influenced by Indonesia's huge solar resource potential year-round, given its location along the equator. As for the Aggressive Carbon Tax scenario, coal capacity remains constant from 2025, which implies that a more aggressive carbon tax rate may limit the capacity and investment for CFPP.



(**a**) (**b**)

Figure 5. Power Plant Capacity, 2015-2050 (GW). (**a**) Least Cost, Coal Phase Out, and Carbon Tax Scenarios; (**b**) NDCs and JETP scenarios.

3.3. CO_2 Emissions

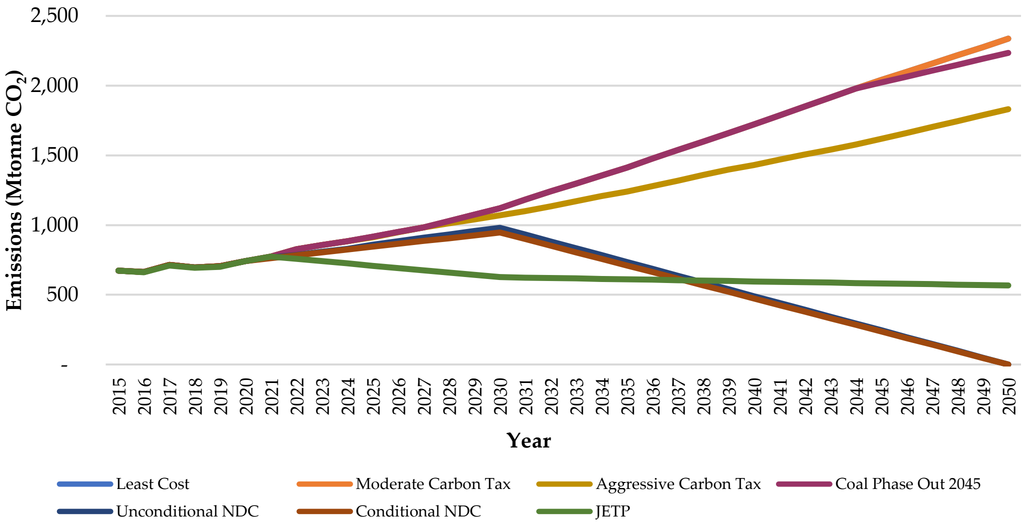


Figure 6. Annual CO_2 Emissions of Modelled Scenarios, 2015-2050 (MtonneCO_2).

The Moderate Carbon Tax and Coal Phase-Out scenario has a similar emission result throughout the period with the Least Cost scenario, peaking at 2,300 MtonneCO_2 in 2050, the highest overall emissions compared to other scenarios. This suggests that Indonesia's proposed carbon tax rate led to an insignificant emission reduction, and a greater emission reduction can only be achieved with earlier CFPP retirement. On the contrary, implementing the Aggressive Carbon Tax scenario alone reduces the overall emissions by 13% compared to the Least Cost scenario, to around 1,800 MtonneCO_2 by 2050.

NDCs and JETP scenarios reduce the overall emissions by 55% and 52% respectively, compared to the Least Cost scenario. In addition, both NDCs have similar emissions results, representing the lowest overall emissions than other scenarios and a rapid decrease from 2030 due to the net zero emissions constraint, as shown in Figure 6. Hence, further emission reduction may be achieved through adopting a similar approach and incorporating net zero emissions target to JETP objectives.

3.4. Investment and Cost

The Least Cost, Coal Phase-Out, and Carbon Tax scenario that are still utilising fossil fuel power plants is allocating 80% of the costs for variable parameters, owing to the fact that fuel cost is comparatively higher than implementing renewable energy technologies. On the contrary, adopting renewable energy may potentially lower the variable costs. The NDCs have the lowest variable cost compared to other scenarios (US$200 billion less than Least Cost scenario) by adding the net zero emissions constraint and deploying huge renewable energy technologies in 2050.

In 2050, the allocation of 88% fixed operating costs in the Least Cost scenario directs toward fossil fuel, a stark contrast to the 5% allocation in the JETP scenario. During the same period, the Aggressive Carbon Tax scenario exhibits the lowest fixed cost at US$6 billion, presenting a notable difference of over US$50 billion from the scenario with the highest fixed cost, NDCs and JETP.

In NDCs and JETP scenarios, 50% of the cost accounts for capital investment of cleaner energy, primarily allocated to develop solar technology. In addition, the overall cost doubled than the Least Cost, Coal Phase-Out, and Carbon Tax scenario. However, with the utmost goal of achieving a just energy transition, the development of renewable energy is crucial albeit requiring huge capital cost to develop the technology and expand the capacity. Therefore, investment funds from JETP play a vital role for Indonesia.

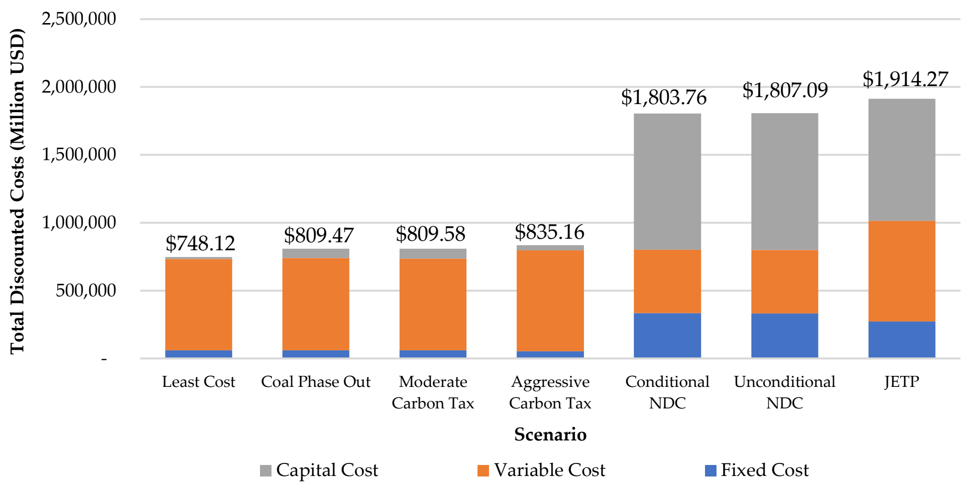


Figure 7. Total Discounted Costs of Modelled Scenarios, 2015-2050 (Million USD).

4. Discussion

4.1. Findings and policy insights

The main barrier to a just energy transition in Indonesia has been the country's continued coal regime, with minimal efforts made to end it. Consequently, renewable energy technologies in Indonesia remain costly, making them non-competitive with fossil fuel prices. This is primarily attributed to the political barriers linked with the stable regime of fossil fuel-based energy – leading to huge fossil fuel subsidy, the reliance on imported fuel, the technical complexities of grid integration in this country with archipelagic geographical situation, and perceptions of high-risk.

JETP targets included in the modelled scenario are renewable energy share, emission reduction, and early retirement of CFPP, in which 2035 is chosen as a more ambitious target compared to the Coal Phase-Out 2045 scenario. Despite excluding the net zero emissions target, this scenario achieves a 19% reduction in emissions by 2030 and a 52% reduction by 2050. Additionally, it surpasses the renewable energy share target, reaching 43% by 2030 (21% solar, 12% hydropower, and 10% geothermal).

Based on the modelling results, if the energy system is focused on the Least Cost scenario without adopting any additional decarbonisation measures, Indonesia will not achieve its NDC objectives for the power sector by 2030. In the Coal Phase-Out scenario, the findings show an increase in natural gas' power generation and capacity, which is another fossil fuel energy source that also emits a high emission ratio. Furthermore, the model chooses renewable energy technologies, including solar, geothermal, and hydropower. This supports the insight from Handayani et al (2022); Reyseliani et al (2022) and PLN's renewable energy targets of energy transition in Indonesia [50,51]. Particularly, solar technology with huge storage capacity is deployed massively to meet the increasing demand, as stated in Reyseliani & Purwanto (2021) [17].

Solar technology, the biggest renewable energy source potential in Indonesia [47], accounts for almost 75% of electricity mix in 2050 in NDC and JETP scenarios. Both scenarios imply that switching to renewable energy technology would come at a significant capital cost – even the expenditure is double that of the Least Cost scenario. This emphasises the need for substantial investment. And with JETP, Indonesia needs to accelerate and prioritise the adoption of renewable energy technologies in the short-term.

In comparison to other countries, Indonesia's proposed carbon tax rate (US$1.98/t$CO_2$e) is relatively lower than the global average. For instance, Japan sets it at US$2.17/t$CO_2$e, Singapore at US$3.77/tCO_2e, Denmark at US$26.53/t$CO_2$e, and Finland at US$57.64/tCO_2e [52]. This suggests that Indonesia has the potential to implement a more aggressive carbon tax rate. And by implementing Denmark's carbon tax rate through Scenario 4 (Aggressive Carbon Tax), it is evident that Indonesia may lower the emission from the power sector by 13% in 2050. This may be levied in Indonesia as an additional measure of the existing decarbonisation targets.

Considering the broader effects of coal decommissioning on businesses, society, and the overall economy, it is pivotal to minimise expenditure and maximise emission reduction. Thus, three suggested short- and medium-term policies are as follows:

- Early CFPP retirement through a policy-based closure, a strategy employed in successful extensive coal decommissioning practices in the UK and US [53] – such policy should be supported with cost-effective mechanisms (as it will drive social reforms, such as employment shift and fostering a significant transition to green jobs revolution), compliance to just transition principles, reforming coal subsidies, and adopting a transparent governance system, cancellation of CFPP construction and repurposing existing CFPP. Indonesia's current CFPP early retirement plan (3 CFPPs with total capacity of 1GW by 2030 and coal phase out in 2050) [54] is insufficient to reach net zero emission by 2050. And despite requiring substantial expense of redevelopment and demolition, opting for early CFPP retirement is a more reasonable choice, especially when considering the long-term consequences of owning a stranded asset.
- Levy a more ambitious carbon tax rate – as Denmark's rate (US$26.53/t$CO_2$e) is estimated to successfully lower 13% emissions by 2050, which aligns with Hartono et al (2023) suggestion of US$28.88/t$CO_2$e carbon tax rate in Indonesia [55]. Moreover, interventions on the macroeconomic scale will be crucial for the success of the transition [56]. Although implementing carbon pricing may have drawbacks on other sectors such as consumption and employment, this should be implemented alongside increased investments in the expansion of renewable energy technologies.
- Accelerate investment on solar technology and storage infrastructure – powering beyond coal would necessitate a dependable and secure energy supply to fulfil the demand. Indonesia's vast renewable energy potential should serve as the backbone of this transition. Because of its geographical condition as an archipelagic nation, Indonesia has to ratify supporting regulations and allocate funds to enhance grid connectivity, ensure grid stability and flexibility, also expand the battery storage capacity, to further maximise solar's enormous potential throughout the year. Other research [33] supports this notion, recommending government prioritisation in the short-term to prevent larger expenditures in the future. Furthermore, this policy may initiate a multiplier effect on investment and encourage behavioural change for a just energy transition.

4.2. Limitations and opportunities of further research

This study acknowledges several limitations and opportunities for future research. Firstly, this study refers to power generation in Indonesia as the whole country and does not consider various transmission grids and several off-grid power plants albeit the archipelagic location of Indonesia. And with the focus of the study is the power sector, it does not include analysis for other sectors such as transportation. Secondly, as the JETP initiative in Indonesia is an evolving area, this study only considers current targets. And with the limitation of the software to produce a feasible model result relative to the net zero target, the JETP scenario in this study does not include net zero constraint.

Thirdly, this study updates the techno-economic data from national institutions such as MEMR and National Energy Agency of Indonesia to provide more precise, accurate, and consistent data instead of generic data from international agencies. Lastly, flexibility and sensitivity analyses are not conducted in this study, yet future studies may incorporate energy system flexibility analysis using additional open-source tools, such as FlexTool. Moreover, social cost analysis may provide additional insights of just energy transition impacts in Indonesia.

5. Conclusions

Through a cost-optimisation energy modelling tool in achieving NDC and JETP targets, this study models several decarbonisation and energy transition scenarios to lower Indonesia's dependence on fossil fuel and to achieve net zero emissions by 2050 or sooner. The scenarios are Least Cost, Coal Phase-Out, Carbon Tax, NDC, and JETP.

With the Least Cost and Moderate Carbon Tax scenario producing a similar overall analysis result, a more aggressive carbon tax rate should be levied. The assessed tax rate (US$26.53/t$CO_2$e) may reduce 13% carbon emissions by 2050. Furthermore, the Coal Phase-Out scenario resulted in a similar renewable energy percentage in the electricity mix as Least Cost and Carbon Tax scenarios, with an addition of significant natural gas generation starting 2045 as the substitute to coal. In terms of cost, NDCs and JETP scenarios are more costly than other scenarios due to the huge capital cost required for replacing coal with renewable energy technologies, exceeding Least Cost's cost by approximately US$1.1 trillion.

With a least-cost approach, the model produces an ideal electricity mix of JETP scenario in 2030 is as follows: 48% natural gas, 21% solar, 12% hydropower, 10% geothermal, 7% biomass, 2% oil, and 0.03% onshore wind. Meanwhile the proposed electricity mix in 2050 includes 76% solar, 20% hydropower, 3% natural gas, and 1% geothermal. Thus, this study emphasises future potential of solar, geothermal, and hydropower deployment with the integration between transmission grids, considering Indonesia's enormous renewable energy potentials in different islands and regions.

Analysis and comparison of various results indicates that achieving Indonesia's NDC and JETP targets necessitates significant investments in renewable energy technologies which will eventually replace existing fossil fuel technologies. Despite that, maintaining the investment in fossil fuel technologies also requires a huge operational and maintenance cost. Thus, investment funds from JETP and a comprehensive just energy transition plan and framework is crucial. To conclude, the suggested key emission reduction pathways for Indonesia are implementing an aggressive carbon tax rate, accelerating coal phase out, and prioritising solar technologies investment.

Predicting future costs, prices, and societal acceptance of new and renewable technologies is a complex task. Due to being a highly evolving sector, the modelling conclusion in this study, which is based on existing regulations, might change in the future. Future research on power transmission grids, other off-grid power plants, social cost, sensitivity, and flexibility analysis of the energy system impacted by the energy transition in Indonesia may be incorporated to address the limitations of this study.

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Data Availability Statement: The data and model code used for this study is fully accessible and licensed under MIT license. Supplementary material is available at Zenodo repository [58].

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U4RIA Compliance Statement: This work follows the U4RIA guidelines which provide a set of high-level goals relating to conducting energy system analyses in countries. This paper was carried out involving stakeholders in the development of models, assumptions, scenarios and results (Ubuntu / Community). The authors ensure that all data, source code and results can be easily found, accessed, downloaded, and viewed (retrievability), licensed for reuse (reusability), and that the modelling process can be repeated in an automatic way (repeatability). The authors provide complete metadata for reconstructing the modelling process (reconstructability), ensuring the transfer of data, assumptions and results to other projects, analyses, and models (interoperability), and facilitating peer-review through transparency (auditability).

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