The role of the energy–carbon–economy nexus and CO_2 abatement cost in supporting energy policy analysis: multi-scenario analysis of a region in Indonesia

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Key Messages

- Indonesia has declared a new and renewable energy (NRE) share target and declared a coal phase-out plan to support the CO_2 emission reduction commitment.
- Supporting policies are required to support the NRE share target and coal phase-out plan, i.e., carbon limitation and carbon tax.
- A carbon limitation of 10,087 million tons with a carbon tax of 67 USD/ton and a carbon limitation of 8,482 million tons with a carbon tax of 77 USD/ton are required to support the NRE target and coal phase-out plan, respectively.

Parameter	Java-Bali
Total area (km²) (BPS,2020)	135,219
Population (in million) (BPS,2020)	138.9
Population growth (%) (BPS,2020)	1.18
Economic growth (%) (RUPTL, 2019-2028)	5.1
Projection of electricity demand growth (%) (RUPTL,2019-2028)	5.77

Java–Bali system will significantly affect the national energy mix because this system holds 74% of national generating capacity and 72.4% of national electricity consumption.

Introduction

The increase in CO_2 emissions impacts global warming and climate change. Concern over this issue has caused various countries to reduce their emissions by formulating policies, especially in the electricity sector [1]. Indonesia also contributes to climate mitigation through national energy planning, electricity planning, and other energy policies. For example, the Indonesian government's Regulation (No.79/2014) established a new and renewable energy (NRE) target of 23% by 2025 and 31% by 2050 [2]. In addition, the government also declared a plan to move toward net-zero emission by phasing out coal power plants [3]. However, these policies are not accompanied by cost-benefit analysis assessing how to reduce emissions cost-effectively.

As the implementation year of coal phase-out is still awaiting the President's decision (options include 2045, 2050, 2060, and 2070), this research assumes 2050 as the implementation year for coal phase-out. This date aligns with other existing policy targets, such as the national energy policy 2050 and the NRE targets 2050.

Indonesia's power system is dominated by coal power plants that have the highest CO_2 emission factor. The emission factor represents the emission produced for each generation of 1 kWh of electrical energy. Therefore, CO_2 emissions reduction can be achieved by replacing coal power plants with NRE power plants or adding to the NRE share in power generation: NRE power plants have much lower emission factors than coal power plants.

However, on average, most NRE power plants have higher generation costs than coal power plants, as shown in **Figure 1**

[4][5][6]. Therefore, adding to the NRE share in power generation will probably increase electricity generation costs and become an obstacle to reducing CO_2 emissions by increasing the NRE share.

For this reason, this policy brief aims to perform a cost-benefit analysis of the energy–carbon–economy nexus through CO_2 abatement in long-term generation expansion planning (GEP). The cost-benefit analysis is helpful in supporting decision-making, because it can provide knowledge of the benefits and costs that can occur. The result will help the Indonesian government determine its carbon limitation and establish a penalty policy.

Case Study Context

Indonesia is an archipelago with separate power systems on each island. The Java–Bali system emits the most CO_2 because seventy-four percent of Indonesia's power plants are located in this system, with the total energy consumed at around 72.4 percent [5]. This system resulted in CO_2 emissions of approximately 171.5 million tons in 2019 with an emission factor of 0.817 tons CO_2/MWh [7]. Therefore, this research focuses on the Java–Bali system as a case study.

Methodology

This policy brief presents a cost-benefit analysis based on the long-term GEP model. The first step in modelling long-term GEP is to develop a reference energy system (RES) depending on the country's existing characteristics. Moreover, RES is simulated in OSeMOSYS energy modelling [8]. OSeMOSYS is an open-source GEP model based on a linear programming method to find the energy generation mix that provides the least-cost solution [9].

This research creates multiple scenarios based on the CO_2 emission reduction limit. The scenarios range from no reduction (i.e., business as usual (BAU)) to a 50% reduction in BAU emissions. Based on the percentage of emission reduc-

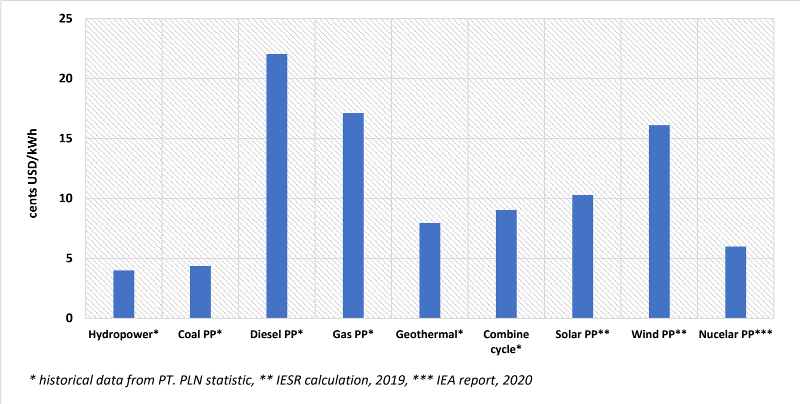

Figure 1 LCOE based on technologies in Indonesia[4][5][6]

Table 1. The Techno-economy parameter [14][15][16]

Power plant	Investment Cost	Fixed O&M Cost	Var. O&M Cost	Capacity Factor	Technical Life
	$/kWe	$/kWe/year	$/MWh	%	years
Diesel PP	600	18	2	25	25
Coal PP	1400	31.3	2	75	30
Gas turbine PP	700	18	1	35	25
Combine cycle PP	850	19.2	1	60	25
Machine Gas PP	800	18	1	55	25
Nuclear PP	5500	138	2	90	40
Geothermal PP	4000	30	1	80	30
Hydro PP	2000	6.6	1	56	50
Wind PP	1800	39.55	0.8	20	27
Solar PP	1200	24.7	0.4	16.7	25

O&M: Operation and maintenance
Fixed O&M cost: All cost incurred to operate and maintain are not affected by the amount of energy produced and are expressed it capacity, e.g. $/kW
Variable O&M (Var O&M) cost: All cost incurred tooperate and maintain which vary with the amount of energy produced and are expressed inper unit energy, e.g. $/MWh

Table 2. Fuel Price [7]

Type of primary energy	Price	
Coal	65	USD/ton
LNG	15	USD/MMBTU
HSD	0.5	USD/Litre
Geothermal	7.6	Cents USD/kWh
Nuclear (U_3O_8)	60	USD/kg

LNG: Liquified Natural Gas, HSD: High Speed Diesel, U_3O_8: Triuranium Octoxide

Table 3. Simulation result for three scenarios: BAU, government NRE target, & coal phase–out compared to BAU in 2050

Scenario in 2050	NRE share (%)	CO_2 emission limitation (Mton)	CO_2 penalty (USD/ton)
BAU	10	No limit	0
Government NRE target	36	10,087	67
Coal phase-out	36	8,482	77

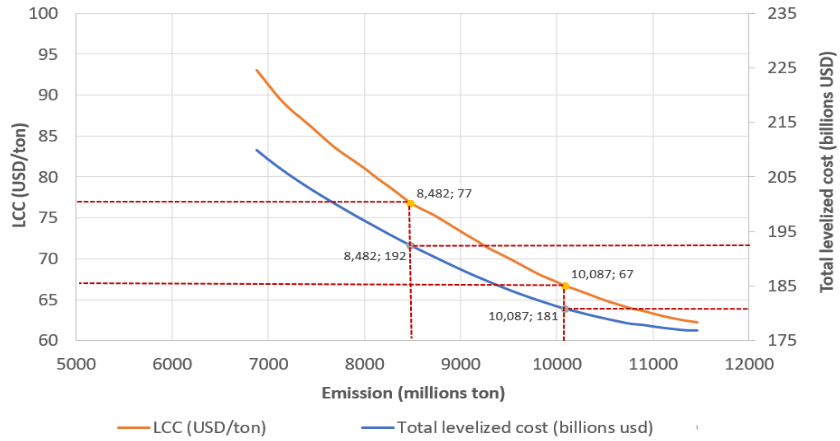

Figure 2. The correlation between LCC, total levelized cost and CO_2 emission

tion in the scenario, emission production can be obtained that can be used as a limitation to support the NRE target and coal phase-out policies. For example, the coal phase-out can be achieved in the 26% reduction scenario. It means that the emission limit required is 74% of the BAU emission. In addition, based on the 26% reduction scenario results, the levelized carbon cost (LCC) and the total levelized generation cost required to support the phase-out coal plan can be obtained.

The NRE share is restricted to a maximum of 80% because the other 20% supports the flexibility of the system. System flexibility is the ability of the system to maintain the balance of supply and demand due to unexpected situations and variability on the supply side [10]. High penetration of RE creates high variability on the supply side. Therefore, system flexibility is essential when the energy system has a high RE share.

The results provide many possible solutions. The optimum solution is evaluated by setting the model to find the least-cost solution considering the energy balance, reserve margin, and CO_2 emission constraint. The energy balance represents the balance between demand, supply, and the ability of generators to produce electricity. Reserve margin represents the reserve capacity of the power plant against peak load to anticipate forced outages and scheduled maintenance of the power plant. The techno-economy parameter of all power plants in the Java–Bali system and their fuel price are shown in **Tables 1 and 2**. This research assumes that the economic parameters of the power plant and the fuel price are fixed in the planning period. This research does not consider the uncertainty of costs.

Finally, a cost-benefit analysis is performed to correlate the adequacy of the energy supply, CO_2 emissions, generation cost, and the levelized carbon cost (LCC). The LCC is a carbon cost that correctly considers the value of time and the possible value of changes in CO_2 reduction over time. The LCC calculation is done by dividing the levelized cost by the levelized CO_2 emission.

The cost of CO_2 abatement represents the cost required to reduce CO_2 emissions. Meanwhile, the correlation between LCC and CO_2 emission provides information on the carbon tax.

Results and Discussion

By conducting a long-term GEP with multi-scenario analysis, the correlation between CO_2 emission reduction, the NRE target, coal phase-out, generation cost, and the LCC in the Java–Bali power system can be obtained, as shown in **Table 3**. Furthermore, the correlation between LCC, total levelized cost, and CO_2 emission is shown in **Figure 2**. The correlation between the total levelized cost and CO_2 emissions provides information on the CO_2 abatement cost.

Table 3 and **Figure 2** show that the NRE share of 31% by 2050 can be reached by implementing a cumulative CO_2 emission limit of ~10,087 million tons and a carbon tax of ~67 USD/ton. The cumulative emission limit is the limit of total emission from 2019 to 2050. This carbon tax is only implemented when the emission produced exceeds the limit. If the emissions produced do not exceed the limit, the carbon tax is not implemented. In this scenario, the coal share decreases from 70% in 2020 to 44% in 2050. Reducing the coal share to achieve the NRE target required an additional levelized cost of 3.95 billion USD compared to the BAU scenario.

Renewable energy resources in the Java–Bali region are limited. Based on the Ministry of Energy and Minerals Resources (MoEMR) data, the potential resources for hydro, geothermal, solar, wind, and nuclear are 9.28 GW, 6.18 GW [11], 35.99 GW, 3.5 GW [12], and 12 GW [13], respectively. In addition, geothermal, solar, and wind energy incur higher generation costs due to the high hot steam prices for geothermal energy and the low-capacity factor for solar and wind energy. Due to these obstacles, achieving the NRE target requires nuclear power plants of 2.09 GW in 2030, as shown in **Table 4**.

The results show that the geothermal power plant is not economically developed due to its high investment costs for geothermal PP, as shown in **Table 2**, and the high cost of the geothermal exploration phase. High

Table 4. The capacity of new and renewable energy power plants

Year	Nuclear			Geothermal			Hydro			Solar			Wind		
	BAU	Gov NRE target	Coal phase-out	BAU	Gov NRE target	Coal phase-out	BAU	Gov NRE target	Coal phase-out	BAU	Gov NRE target	Coal phase-out	BAU	Gov NRE target	Coal phase-out
2020	0	0	0	2.12	2.12	2.12	3.60	3.60	3.60	0	0	0	0	0	0
2025	0	0	0	3.08	3.08	3.08	9.22	9.22	9.22	0	0	0	0	0	0
2030	1.13	2.09	2.09	2.70	2.70	2.70	9.16	9.16	9.16	0	0	0	0	0	0
2035	2.61	2.61	9.04	2.64	2.64	2.64	8.77	8.77	8.77	0	0	0	0	0	0
2040	3.13	12	12	2.17	2.17	2.17	7.64	7.64	7.64	0	0	26.57	0	0	3.50
2045	3.65	12	12	1.28	1.28	7.46	7.59	7.59	7.59	0	16.88	35.99	0	3.502	3.50
2050	4.17	12	12	1.11	7.29	7.29	7.04	7.04	7.04	0	35.99	35.99	0	3.502	3.50

investment in the exploration phase is also revealed from the statistical data on power generation fuel prices in Indonesia [7], which shows the price of geothermal hot steam reached averages of 7.6 cents USD/kWh. Solar and wind are not economically developed because of high investment costs and low capacity factors. The high investment cost is due to low local content. The lower local content affects higher import duties and taxes. The low capacity factor is caused by the characteristic of solar irradiation and wind speed in Java–Bali.

Geothermal, solar, and wind energy becomes economically developed in the government NRE target and coal phase-out scenarios when hydro and nuclear energy reach their maximum potency. The order of NRE power plants in the Jawa-Bali system based on their economy is as follows: hydro, nuclear, wind, solar, and geothermal energy.

Nuclear energy is economically developed because it has lower generation costs than geothermal, solar, and wind energy. Nuclear power plants are the second cheapest NRE generator after hydropower plants. Therefore, it is used after all practical sources of hydro energy are utilized. Nuclear power plants are currently mentioned in national energy policy as the last option in the NRE share. However, developing nuclear energy requires a strong commitment from the government.

In the coal phase-out scenario, CO_2 emissions will reduce by 26% (~2,980 million tons of CO_2) compared to BAU. This scenario indicates that the share of NRE by 2050 will reach 36%. A cumulative CO_2 emission limit of ~8,482 million tons and a 77 USD / tons carbon tax are required. Coal phase-out required an additional levelized cost of 15.53 billion USD compared to the BAU scenario. Similar to achieving the NRE target, the coal phase-out scenario requires nuclear power plants in 2030.

In addition, because of the limitation of the NRE resources, the combined-cycle power plant is used to replace the coal power plant after all resources of NRE are used. As a result, the energy share of the combined-cycle power plant reaches 19% by 2050 in the BAU and government NRE target scenarios. On the other hand, in the coal phase-out scenario, the energy share of the combined-cycle power plant reaches 62% by 2050. The combined-cycle power plant is fuelled by Liquified natural gas (LNG). Therefore, to support the coal phase-out plan requires 3.26 times LNG consumption compare to the BU scenario.

The significant increase in LNG consumption creates a sizeable increase in costs as well. Therefore, to decrease the cost, an alternative strategy is needed to achieve the target of NRE sharing and coal elimination. The option of interconnection with Sumatra, Kalimantan and East Nusa Tenggara islands with abundant NRE resources is a potential alternative to achieve the targets. By importing the NRE through the interconnection line, it is hoped that the generation cost can be decreased. In addition, this analysis uses a static RE cost that does not reflect possible future cost reductions. On the other hand, the RE costs are likely to continue falling. Therefore this could reduce the increase in gas power plants.

Recommendations

This research provides several recommendations as follows:

- To support new and renewable energy (NRE) share target and coal phase-out plan in the Java–Bali system, the government needs to consider strategic policies relating to CO_2 reduction.
- Government policies should clearly define the CO_2 emission threshold (carbon limitation) and implement a carbon tax for electricity generation companies accordingly.
- Electricity generation companies should pay penalties if they produce CO_2 emissions that are greater than the government threshold.
- Our research suggests that a cumulative CO_2 emission limit of ~10,087 million tons and a carbon tax of ~67 USD/ton are needed to achieve the NRE target.
- Our research suggests that a cumulative CO_2 emission limit of ~8,482 million tons and a carbon tax of ~77 USD/ton are needed to achieve the coal phase-out plan.

- Achieving the coal phase-out and NRE targets requires strong commitment and an immediate government decision to utilize nuclear energy.
- The government of Indonesia should guarantee the adequacy supply of Liquified Natural Gas (LNG) with its economical price to support the coal phase-out plan
- It is necessary to look for alternatives to fulfil the long-term demand projection through interconnection with other islands with immense renewable energy sources, e.g., Sumatra, Kalimantan and East Nusa Tenggara, to achieve the target of NRE share and coal phase-out.

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Notes

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