
The Impacts of Emission Reduction Targets in Indonesia Electricity Systems: An Energy-Economy-Environment Model Simulation

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Abstract. Climate change policy often contradicts the least-cost objective of electricity generation in developing countries. The objective of our study is to propose electricity generation mixes that can meet emission reduction targets in Indonesia. We estimate the optimal generation mix, costs, and emissions from three scenarios, namely existing power plant planning, and 11% and 14% emission reductions in Indonesia's electricity sector. The estimations are based on linear programming, input-output analysis, and life-cycle analysis, integrated into an agent-based modeling (ABM) platform. The simulation results confirm the existing power plant planning, which is dominated by coal-based power plants, as the lowest-cost scenario in the short-term; however, this scenario also produces the highest emissions. Emission reduction scenarios have lower emissions due to a higher share of renewables and, therefore, the Indonesian electricity system is robust from fossil fuel price increases. In the long-term, costs incurred in the emission reduction scenarios will be lower than electricity generation costs under the existing power plant planning. Our findings should be a basis for re-evaluating energy policies, power plant planning, and the research agenda in Indonesia.

Keyword: linear programming, agent-based modelling (ABM), input-output analysis, life-cycle analysis

1. Introductions

Renewable energy is a crucial technology to reduce emissions in the energy sector (Al Irsyad, Halog, & Nepal, 2019b; GOI, 2017b) and, therefore, the government sets a renewable energy target for 23% of total energy supply in 2025 (GOI, 2014). However, regulated and monopolized electricity markets have hampered renewable energy expansion in developing countries like Indonesia. The Indonesia government only allows one power utility in a region and controls the electricity prices. Several private power utilities (PPUs) supply electricity to industrial estates; meanwhile, some remote areas without electricity grids of the State-owned Electricity Company, or Perusahaan Listrik Negara (PLN), are served by local PPUs that usually cannot afford the required business permits. PLN has the largest monopoly rights and, therefore, an obligation to provide an electricity supply. The government maintains low electricity prices and, consequently, an electricity subsidy is required since the average PLN energy production cost is higher than the average electricity prices. Increasing fossil fuel prices force the government to reduce the electricity subsidy, and one of the policies taken is to use renewable energy tariffs that are less than the costs of oil-based electricity generation (MEMR, 2017). The government has argued that global prices of renewable energy technology are declining as indicated by a low solar price obtained in a Dubai solar farm auction in 2016. On the other side, renewable energy industries have reconsidered their investment plan since the investments become risky and uncertain under the new policy (Maulidia, Dargusch, Ashworth, & Ardiansyah, 2019).

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This research aims to estimate the generation cost changes due to the implementations of emission reduction targets in the 15 largest electricity systems in Indonesia. We analyze three scenarios of power plant expansion, i.e., the PLN's electricity supply business plan (RUPTL) 2016 to 2025, and two scenarios of 11% and 14% emission reduction targets. Previous studies have analyzed the interaction of renewables and emission reductions in the Indonesian electrical system, but their scope of analysis is limited to a single electricity grid system or focused on the aggregated national level (Al Hasibi, Hadi, & Widiastuti, 2013a; Handayani, Krozer, & Filatova, 2017; Kumar, 2016; Tanoto & Wijaya, 2011; Utama, Ishihara, & Tezuka, 2012; Wijaya & Limmeechokchai, 2009, 2010). This study also contributes to the energy modeling literature. Most previous studies have used conventional bottom-up energy models while our study uses agent-based modeling (ABM) to provide an energy model framework that can explore the interactions of the least-cost strategy practiced by PLN and the government with the maximum profit strategy applied by independent power producers (IPPs). As a pioneering model, the current model version cannot analyze the interactions yet due to time and data availability limitations. Future studies should incorporate a power plant expansion analysis with behavioral economics theory in modeling interactions of IPPs, PLN, and the government.

The organization of the paper is as follows: Section 2 reviews previous studies analyzing power plant expansions in Indonesia. Section 3 explains the energy modeling approach, data, and policy scenario. Section 4 discusses the results of simulations and sensitivity analysis, and Section 5 presents the policy discussions and conclusions.

2. Literature Review

A study designing the lowest costs of power generation is crucial for developing countries to meet growing electricity demands and to participate in global emission reduction actions. For this purpose, most of Indonesia's studies used the Long-range Energy Alternatives Planning (LEAP), the most recommended energy model for analysis in developing countries (Bhattacharyya & Timilsina, 2010). Originally, LEAP was an accounting-based simulation model but, since 2012, it has been integrated with the Open Source Energy Modeling System (OSeMOSYS), a linear programming kit. Recent LEAP studies have used the OSeMOSYS feature (Al Hasibi, Hadi, & Widiastuti, 2013b; Handayani et al., 2017; Kumar, 2016) while older studies used the primary feature of LEAP (Tanoto & Wijaya, 2011; Wijaya & Limmeechokchai, 2009, 2010). Before OSeMOSYS, optimization analysis in LEAP was conducted by using external optimization software such as General Algebraic Models (GAMS) (Utama et al., 2012). Most LEAP-based studies analyzed emission reductions as a result of simulations except for Handayani et al. (2017) who applied the emission reduction target as a constraint in an optimization analysis of power plant expansion. Moreover, the focus of previous LEAP studies was the largest electricity system (i.e., the Java-Madura-Bali (JAMALI) system) and only two studies analyzed power plant expansions at the national level (Kumar, 2016; Utama et al., 2012).

Several more advanced commercial energy models have also been used for simulating optimal power plant expansion in Indonesia. PLN is using the Wien Automatic System Planning (WASP) model for stating the official plan of power plant expansion in RUPTL (PLN, 2016a). The Market Allocation (Markal) model is another widely known energy model and it was used by Das and Ahlgren (2010) to analyze power plant expansion in Indonesia under an emission reduction target. A similar analysis was also conducted by Siagian, Yuwono, Fujimori, and Masui (2017) who used the Asia-Pacific Integrated Model/Computable General (AIM/CGE) model.

One of the emerging modeling methods is agent-based modeling (ABM), which offers more features for analyzing energy systems in developing countries (Al Irsyad, Halog, Nepal, & Koesrindartoto, 2017). In this regard, ABM can model socioeconomic issues, such as income disparity and energy access inequality, which influence energy demand and supply (Al Irsyad, Halog, & Nepal, 2018a; Smajgl & Bohensky, 2013). The current trend in ABM studies is to incorporate linear optimization, and some include PowerACE-ResInvest and PowerACE-Europe energy models for analysis in developed countries (Ma & Nakamori, 2009; Pfenninger, Hawkes, & Keirstead, 2014). Thus, we attempt to enrich

energy system modeling by optimizing power plant expansion in Indonesia under the Netlogo platform, a free ABM software. Other contributions to the electricity system literature in Indonesia include the approaches of 1) input-output analysis (IOA) to estimate new economic outputs from each proposed scenario; 2) life-cycle analysis (LCA) to evaluate environmental impacts during the power plant construction stage; and 3) techno-economic analysis (TEA), i.e., revenue requirement (RR), which considers construction costs instead of using overnight capital costs.

3. Methodology, Data, and Policy Scenarios

3.1 Methodology

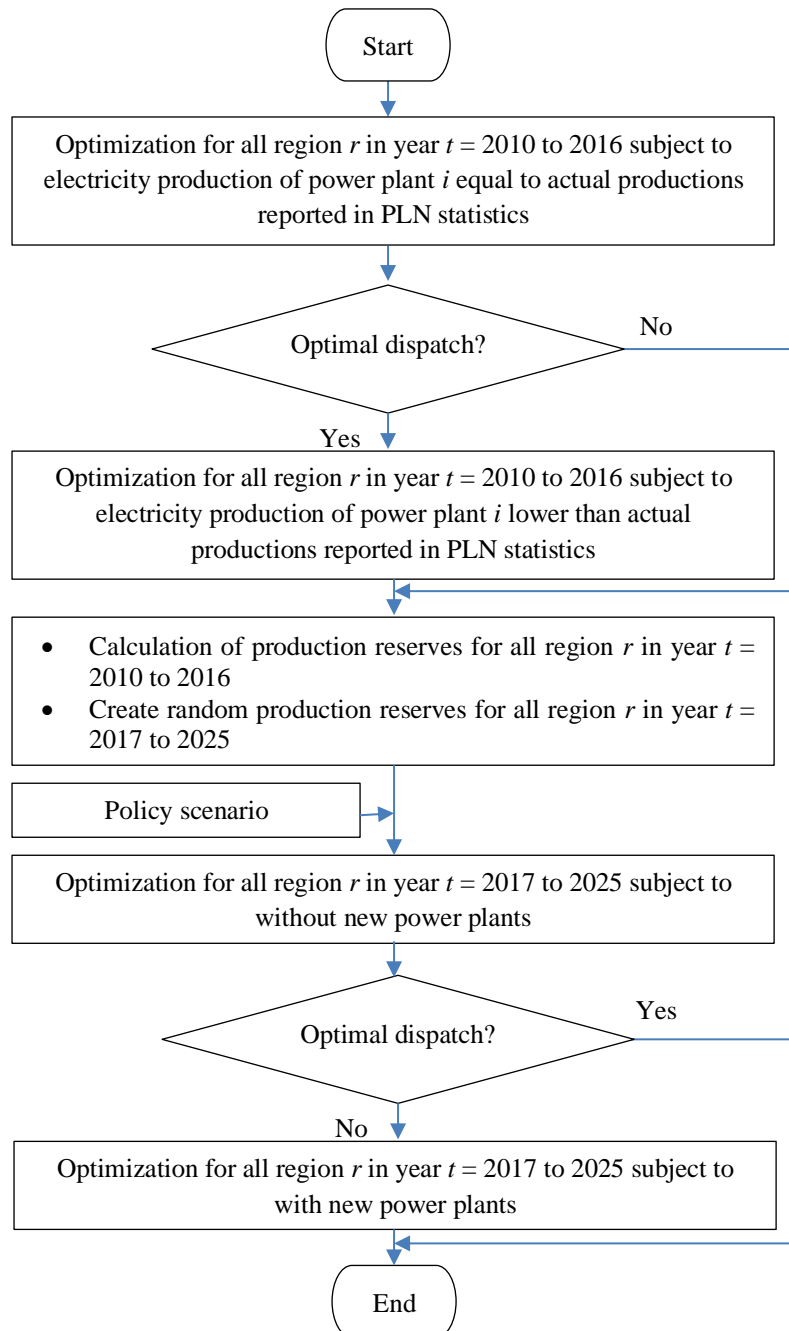


Figure 1. Optimization algorithm in PowerGen-ABM.

The developed model, called Power Generation in ABM (PowerGen-ABM), is operated by using Netlogo and its extensions, including a linear programming solver (MacKenzie, 2016; Wilensky, 1999). The entities in the model are power plants, technologies, and regions, which have a function as data storage. Technology entities contain data of existing power plants and future technologies. Power plant entities possess the operational data of power plants, and region entities handle sectoral electricity demands and regional simulation outputs. Future studies should include the entities of IPPs, PLN, and the government to model investment decision behaviors of those entities.

The initial procedure is to open database of technology, existing and planned power plant capacities, and regional electricity demand data ranging from 2010 to 2025, and to adjust the demand by using demand scenarios and then convert the adjusted electricity demand to daily demands in baseload, cycle load, and peak load durations. Demand adjustment is the re-calculation of electricity demands by considering estimated elasticities in Al Irsyad, Halog, and Nepal (2018b) and shocks in energy price, urbanization, and number of customers, e.g., improvements in the electrification ratio. Total electricity demands in a year are transformed into daily electricity demands in baseload, cycle load, and peak load durations.

Figure 1 shows that PowerGen-ABM applies two optimization types, i.e., linear programming and a heuristic approach. Firstly, optimization problems from 2010 to 2016 use a strict constraint that the optimal electricity production should be equal to the actual electricity production in PLN's statistics; however, optimization problems in some regions cannot be solved due to data inconsistency issues. In this case, the model does a re-optimization by allowing an optimal power plant production that is lower than the actual electricity production. Optimization problems from 2010 to 2016 provide electricity production reserve data, which is the data to generate random production reserves for analysis from 2017 to 2025. Policy scenarios on emission reduction targets can only intervene in optimization problems from 2017 to 2025. The model solves the optimization problem without unplanned new power plants. The model allows unplanned new power plants in the optimization problem if no optimal solution is found. For simplicity, we assume that PLN has a financial limitation and, therefore, all unplanned new power plants will be constructed by IPP. The objective of the optimization is to minimize the generation costs at each electricity system subject to the following constraints:

- a. Minimum electricity generation to satisfy electricity demands in each load type and electricity supply losses;
- b. Maximum electricity generation of each power plant;
- c. Minimum electricity generation of power plants owned by IPPs as stated in the power purchase agreement (PPA) between PLN and IPP;
- d. Renewable energy availability;
- e. Maximum electricity generation share from intermittent renewable energy in an electricity system;
- f. Emission targets.

The optimization outputs are then categorized to monetary values and physical values of new power plant investments, electricity production, and loan interest payments. The monetary values are inputs for IOA, which use the Leontief Inverse Matrix that has 11 power plant technologies (Al Irsyad, Halog, & Nepal, 2019a). The physical values are included for LCA by multiplying the values with environmental factors. For TEA, the study modifies a RR calculation by UCDavis (2016). The modified RR formula includes the effects of construction duration on construction costs, IOA, and LCA. The construction periods of power plants are assumed as linear distributions as in IEA and NEA (2015). PowerGen-ABM, data, and its overview, design concepts, and details (ODD) are archived on the CoMSES Net website (Al Irsyad, Halog, Nepal, & Koesrindartoto, 2019).

3.2 Data

The primary data is yearly PLN statistics from 2010 to 2016 (PLN, 2011, 2012, 2013, 2014, 2015, 2016b, 2017) providing data for regional and sectoral electricity demands, peak loads, power plant capacity, electricity production, and related costs. PLN (2016a) provides a projection for sectoral

electricity demand, peak loads, and planned power plants from 2016 to 2025. Table 1 shows cost data that is mostly from Handayani et al. (2017) and IEA and NEA (2015) for the cost data of biomass. The assumption of future fuel prices is based on prices in PLN (2017) and electricity price growth in IEA (2017) scenarios. Emission factors of electricity systems from 2010 to 2014 are obtained from DGE (2015). BAU emissions data for 15 electricity systems from 2010 to 2025 are calculated using the emission factors, electricity production, and their forecasts. Data for emission factors of power plant technologies are derived from an intensive review of studies that provide emission data of power plant construction and electricity production stages. The selected literature are Tahara, Kojima, and Inaba (1997) for emissions in coal power plant (PP), OCGT, hydro PP, photovoltaics (PV), and oil PP; Sullivan, Clark, Han, and Wang (2010) for emissions in OCGT, geothermal PP, and biomass PP; Eberle et al. (2017) for emissions in geothermal PP; Ghenai (2012) for emissions in wind PP; and Cherubini, Bargigli, and Ulgiati (2009); Koroneos and Nanaki (2012); Meier (2002) for emissions in waste to energy PP. The assumptions of ramp rates of power plants are based on Gonzalez-Salazar, Kirsten, and Prchlik (2017). The ramping rate is related to power plant ability to serve peak, cycle, and base loads. In this article, we assume the minimum ramping rates of power plants to serve peak and cycle loads are 10% and 5%, respectively. Another assumption is 20% as the maximum share of intermittent renewables in an electricity system. The assumption follows the finding by Zakeri, Syri, and Rinne (2015) who recommend 19% as the maximum share of wind energy in the Finnish electricity system.

3.3 Policy Scenario

This study simulates three scenarios to compare emissions, electricity production costs, and energy mixes in peak, cycle, and base loads from each scenario. The first scenario is power plant expansions stated in RUPTL 2016 to 2025 (PLN, 2016a), which plans to build new power plants with a total capacity of 73,061 MW. The remaining scenarios aim to re-evaluate the alternative least costs of power plant expansions with emission reduction targets. Consequently, the emission reduction scenarios exclude any planned new power plants in RUPTL and re-determines the least-cost power plant composition with emission reduction constraints set at 11% and 14%, respectively. The average results for each scenario are derived from 500 simulations.

Table 1. Main assumptions in PowerGen-ABM.

Power plant (PP) technologies	Overnight cost (USD/ kW)	OM cost (USD/ MWh)	Fix OM cost (USD/MW)	Emissions (kg CO ₂ / MWh)	Ramp rate (%full load/min)
Coal PP	1,867	3.8	64,000	1,236.3	6
CCGT	817	3.8	24,000	486.7	8
OCGT	439	38.0	21,000	563.0	20
Geothermal PP	2,675	0.7	53,000	73.2	5
Hydro PP/ MHP	2,200	3.8	56,000	17.1	15
Wind turbine	3,350	3.8	67,000	0.9	0
Waste to energy (WTE)	1,756	0.8	44,000	347.2	20
Biomass PP	5,718	99.0	-	114.4	8
Solar PP	2,228	6.5	78,000	148.0	0
Oil PP	1,953	0.4	20,000	755.7	20

4. Results

Though PowerGen-ABM has features of IOA and LCA, the following discussion of the results will focus on the nexus of emission reduction targets, electricity production mix, and generation costs. All scenarios can achieve an emission reduction target in 2025, as shown in Figure 2(a). Emissions under the RUPTL scenario exceeds BAU emissions from 2017 to 2021 but, then, the emission has declining growth rates and reaches 85% of 507 MtCO_{2e} BAU emissions in 2025. However, optimal electricity production under the RUPTL scenario, as shown in Figure 3(a), cannot meet the renewable energy target since electricity production share from renewables is only 18.1% of the 526-TWh total electricity production in 2025. In contrast, both emission reduction scenarios have lower emissions, reaching 64% of BAU emissions in 2025. Coal-based electricity production still dominates the energy mix in 2025 under the RUPTL scenarios and accounts for 54% of total electricity production, but its share reduces to 42% under the emission reduction scenarios. Renewable energy productions in all emission reduction scenarios exceed 42% of total electricity production in 2025, which is beyond the renewable energy target. The emission reduction scenarios boost the geothermal production share in 2025 from 7.9% in the RUPTL scenario to 17%, as shown in Figure 3(b) and 3(c). Wind-energy productions in 2025 are also significantly different between scenarios. RUPTL concludes 320 MWh wind energy productions while emission reduction scenarios obtain 71 GWh.

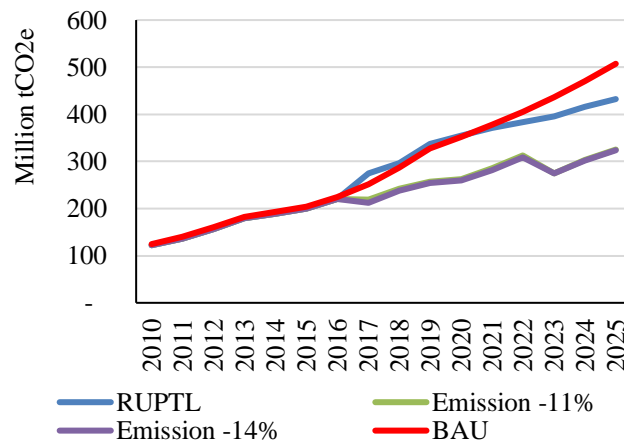


Figure 2. Emissions in operational stages.

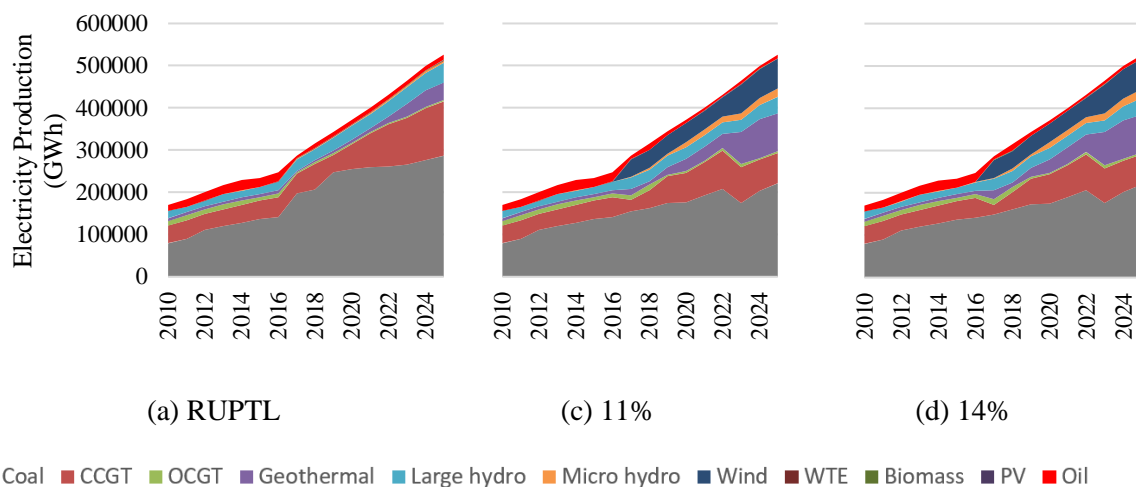


Figure 3. Electricity production mix in 2025.

Table 2 compares the supply allocations of the produced electricity for peak, cycle, and base loads in 2016 and 2025 for all scenarios. In 2016, the peak load was mainly served by OCGT and oil PP;

however, this pattern gradually changes. Under emission reduction pressures, hydro PP and MHP become feasible technologies to serve peak loads, thus reducing the role of OCGT and oil PP as peaking power plants. The higher ramping rates of hydro PP and MHP will also place them as crucial load followers, along with coal PP and CCGT, to serve the cycle load. Power plants serving the baseload are slightly different in the RUPTL and emission reduction scenarios. Electricity from coal PP still dominates the supply of base loads in all scenarios. The RUPTL scenario has higher electricity production from CCGT, hydro PP, MHP, and WTE PP compared to the emission reduction scenarios. The most significant difference is that the emission reduction scenarios have higher electricity production from wind PP, especially in the JAMALI and Papua electricity systems, as shown in Figure 4.

Figure 4 shows regional electricity production mixes in 2016 and 2025 for all scenarios. Based on RUPTL 2016–2025, PLN successfully reduces electricity production from oil PP in most of the electricity systems except in Riau Archipelago, Bangka Belitung, Southeast Sulawesi, Maluku, North Maluku, and Papua (see Figures 4(a) and 4(b)). Among those regions, the emission reduction scenarios lead to a lower electricity production share from oil PP than that of RUPTL in Southeast Sulawesi and North Maluku by increasing electricity production from CCGT and geothermal PP. On the other hand, the emission reduction scenarios have higher electricity production from oil PP in West Nusa Tenggara compared to that in RUPTL. The emission constraints cause this higher oil share because the RUPTL scenario mainly relies on coal PP to supply electricity on West Nusa Tenggara.

Table 2. Electricity production pattern in each load types.

Power production (GWh)	2016			RUPTL in 2025			11% scenario in 2025			14% scenario in 2025		
	Peak	Cycle	Base	Peak	Cycle	Base	Peak	Cycle	Base	Peak	Cycle	Base
Coal PP	0	42269	99103	0	125916	158504	0	108200	113688	0	106442	113172
CCGT	0	20703	26499	0	54601	72808	0	66179	4213	0	65126	4863
OCGT	468	2551	5814	3	1988	1762	331	3497	1439	311	3830	1478
Geothermal PP	0	0	7611	0	0	41196	0	0	89775	0	0	89771
Hydro PP	1	15320	4332	345	35439	10621	340	31730	7211	385	31062	7224
MHP	0	644	105	429	4096	406	52	18698	139	27	22515	154
Wind PP	0	0	0	0	0	320	0	0	71436	0	0	72117
WTE PP	0	98	54	1	658	194	0	184	0	0	184	0
Biomass PP	0	6	165	0	422	519	0	58	412	0	58	412
Solar PP	0	0	9	0	0	299	0	0	33	0	0	33
Oil PP	216	12981	8333	40	10769	1100	100	6710	990	104	7279	1609
Total	685	94572	152025	818	233888	287729	822	235254	289337	827	236495	290834

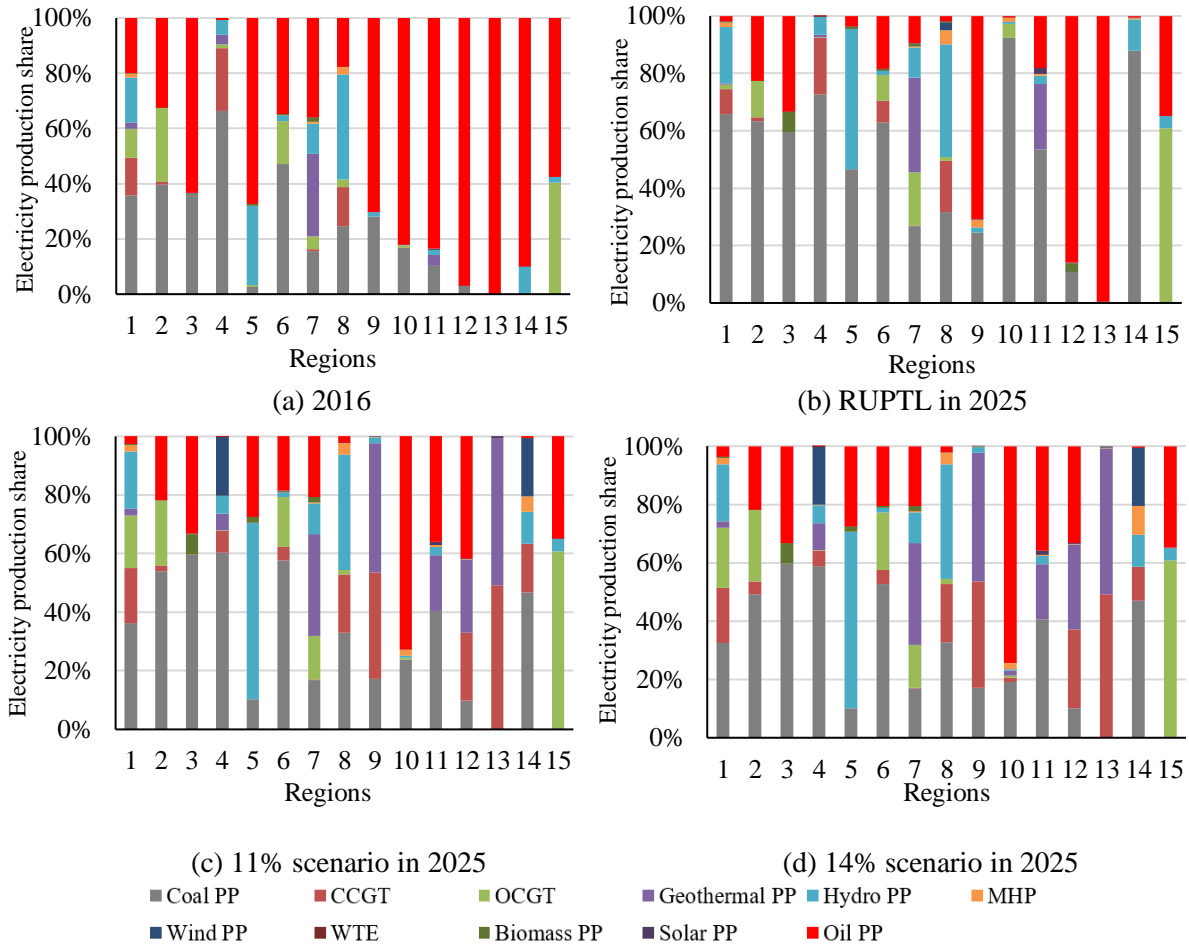


Figure 4. Electricity production mix in each region.

Region number: 1: Sumatera, 2: Riau Archipelago, 3: Bangka Belitung, 4: Java, Madura & Bali (Jamali), 5: West Kalimantan, 6: South Kalimantan, East Kalimantan, North Kalimantan and Central Kalimantan, 7: North Sulawesi & Gorontalo, 8: South Sulawesi, Central Sulawesi and West Sulawesi, 9: Southeast Sulawesi, 10: West Nusa Tenggara, 11: East Nusa Tenggara, 12: Maluku, 13: North Maluku, 14: Papua, and 15: West Papua

PLN’s effort to reduce the share of oil-based electricity production in RUPTL will decrease average generation costs, as shown in Figure 5. The average cost will decrease from 68.8 USD/MWh in 2016 to 52.8 USD/MWh in 2017, although the cost will gradually increase again to 66.3 USD/MWh in 2025 due to rising fixed OM costs of PLN’s new power plants. The average generation costs of the 11% and 14% emissions reduction scenarios in 2017 also reduce to 56.7 USD/MWh and 57.6 USD/MWh, respectively. However, generation costs in the emission reduction scenarios from 2020 onwards increase, reaching 60.1 USD/ MWh and 60.2 USD/ MWh in 2025 for 11% and 14% emission reduction scenarios, respectively.

Table 3 shows the optimal costs of electricity generation in each region. RUPTL 2016–2025 will reduce production costs in most of the electricity systems due to the declining share of oil-based electricity production, as shown in Figure 4. Electricity systems of Bangka Belitung, Southeast Sulawesi, East Nusa Tenggara, Maluku, North Maluku, and West Papua are an exception since PLN will maintain oil-based electricity production in these systems. On the other hand, the shares of oil-based electricity production in the emission reduction scenarios are lower (i.e., 1.6% in 2025) than in the RUPTL scenario, as shown in Figure 4. Thus, all regions under emission reduction scenarios have lower generation costs in 2025 than costs in 2016 and, indeed, most regions have lower generation costs than costs in the RUPTL scenario. For example, since Southeast Sulawesi and North Maluku in the emission

reduction scenarios do not have oil-based electricity production (Figure 4), electricity generation costs of these regions in 2025 reduce from 86.4 USD/ MWh and 203.2 USD/ MWh, respectively, in the RUPTL scenario to 63 USD/ MWh and 65 USD/ MWh in the emission reduction scenarios.

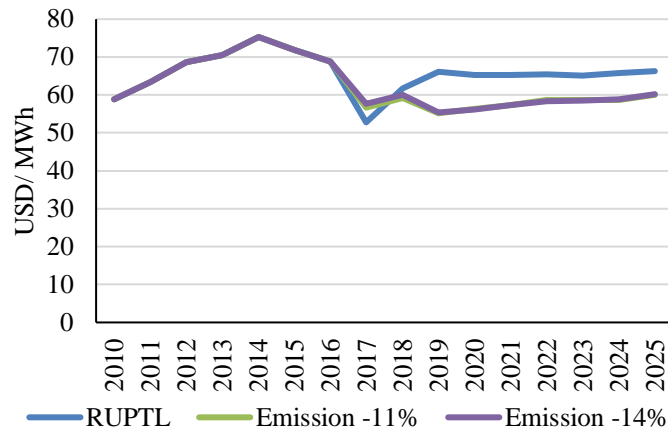


Figure 5. Average electricity production costs.

Table 3. Electricity generation costs (USD/ MWh) in 2016 and 2025 for all scenarios.

Regions	2016	2025		
		RUPTL	11% Scenario	14% Scenario
1	85.3	61.7	55.5	55.7
2	129.2	122.2	96.3	96.5
3	95.4	205.2	89.8	89.8
4	60.9	62.9	57.2	57.2
5	92.3	87.6	67.1	67.1
6	98.9	57.1	83.8	83.9
7	104.6	62.8	76.4	76.2
8	68.1	52.8	60.5	60.4
9	101.7	86.4	63.6	63.3
10	107.6	53.2	63.1	67.4
11	114.1	52.8	63.7	63.7
12	121.5	306.6	108.0	115.3
13	122.3	203.2	65.6	65.5
14	110.2	79.9	98.4	106.8
15	115.9	232.4	71.5	71.8

5. Policy Discussion and Conclusions

This study aims to understand the effects of emission reduction targets on power plant expansion and generation costs. For this purpose, a novel linear optimization algorithm was integrated into an agent-based modeling framework to analyze three scenarios of power plant expansion, i.e., official power plant expansion as stated in PLN’s electricity supply business plan (RUPTL) from 2016 to 2025, and two alternative scenarios related to 11% and 14% emission reduction targets.

The results show that power plant expansion in RUPTL 2016–2025 cannot meet emission reduction targets in the short-term. Renewable energy capacity is projected to grow significantly after 2020 and, therefore, emission growth in 2017 to 2020 will be higher than the current emission growth in the electricity sector. The RUPTL scenario also produces the lowest generation costs in the short-term. Over time, however, the costs will be higher than emission reduction scenarios due to the increases in

fossil fuel prices and fixed OM costs in PLN's new power plants. Nevertheless, all scenarios suggest that coal is still the most cost-effective option in the Indonesian electricity sector. This finding calls for the accelerated commercial implementation of clean coal technologies, which are currently in pilot projects in Indonesia. Renewable energy may have higher costs in the short-term, but the costs can still be covered by the reference tariffs that are relatively high due to the high share of oil-based electricity production. Therefore, the power plant expansion plan in RUPTL should be transformed by minimizing the oil PP share and maximizing renewables, especially geothermal, wind energy, and micro-hydro.

These findings have several policy implications. The government has changed geothermal policies several times to encourage investments (GOI, 2016; MEMR, 2011, 2012b, 2014, 2017), indicating that the government already shows interest in geothermal development. Geothermal capacity in Indonesia in 2018 was the second largest in the world and is just slightly below the geothermal capacity target (DJK, 2018; GOI, 2017a; REN21, 2019). In contrast, the government should increase the development of wind-energy and micro-hydropower plants. The significant policy issues for these technologies are the premium feed-in tariff (MEMR, 2012a, 2015) and, unfortunately, in 2017, they were replaced by tariffs that were lower than oil-based electricity generation costs (MEMR, 2017). Prospects of wind-farm investments are growing after the successful operation of the 75 MW Sidrap wind-farm in South Sulawesi since 2018. The government should anticipate it by intensifying wind-energy surveys and preparing national wind-energy industries. On the other hand, local micro-hydro industries are more mature than the wind-energy industry. Micro-hydro industries actively work in a rural area without national electricity grids and, because of that, their business is often threatened by grid extension plans of PLN and the government. In this case, rural households will shift to the more stable PLN electricity supply while the micro-hydro industries cannot sell their electricity production to PLN due to high interconnection costs. Therefore, the government should hear and solve problems faced by micro-hydro industries to have a more sustainable electricity supply in the future.

Regarding our energy model, PowerGen-ABM has several drawbacks that need further development. The expectation of the integration of a linear programming algorithm in the well-known free ABM software Netlogo is the ability to analyze the interactions of the cost minimization strategy by PLN and the government with the profit maximization strategy by IPPs. The current version of PowerGen-ABM does not have this feature. It merely assumes that PLN does not have adequate investment funding and, consequently, IPPs will construct all new power plants. This assumption should be revised by considering the investment portfolios of PLN and IPPs. Moreover, the optimization algorithm only uses existing power plants to satisfy electricity demands and it will use new power plant technologies in the optimization problem only if the electricity demands cannot be filled by existing power plants. As a result, the algorithm may maximize the economic returns of power plant investment, but it may not give the minimum electricity production costs in the long-term. Future studies should evaluate this algorithm when allowing new power plants to replace old and inefficient power plants even though existing power plants can still produce adequate electricity to meet demands.

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