

Trade-offs between electrification and climate change mitigation: An analysis of the Java-Bali power system in Indonesia



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HIGHLIGHTS

- The Indonesian power sector pathways for meeting the Paris target are proposed.
- Meeting electrification goals under current energy mix triples the CO₂ emissions.
- The proposed CO₂ mitigation scenarios satisfy the Paris climate target.
- Total costs under climate mitigation efforts equal 0.1% of GDP.
- Cost-effectiveness of the CO₂ mitigation scenarios is 14.9–41.8 US\$/ton CO₂e.

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ABSTRACT

The power sector in many developing countries face challenges of a fast-rising electricity demand in urban areas and an urgency of improved electricity access in rural areas. In the context of climate change, these development needs are challenged by the vital goal of CO₂ mitigation. This paper investigates plausible trade-offs between electrification and CO₂ mitigation in a developing country context, taking Indonesia as a case study. Aligned with the 2015 Paris Agreement, the Government of Indonesia has announced its voluntary pledge to reduce 29% of its GHGs emissions against the business as usual scenario by 2030. 11% of this should be attained by the energy sector. We incorporate the Indonesian Paris pledge into the modelling of capacity expansion of the Java-Bali power system, which is the largest power system in Indonesia. The LEAP model is used for the analysis in this study. Firstly, we validate the LEAP model using historical data of the national electricity system. Secondly, we develop and analyse four scenarios of the Java-Bali power system expansion from the base year 2015 through to 2030. These include a reference scenario (REF) to reflect a continuation of the present energy mix (REF), then a shift from coal to natural gas (NGS) (natural gas), followed by an expansion of renewable energy (REN) and, finally, the least-cost option (OPT). The shift to natural gas decreases future CO₂ emissions by 38.2 million ton, helping to achieve the CO₂ mitigation target committed to. Likewise, an escalation of renewable energy development in the Java-Bali islands cuts the projected CO₂ emissions by 38.9 million ton and, thus, assures meeting the target. The least-cost scenario attains the targeted emission reduction, but at 33% and 52% lower additional costs compared to NGS and REN, respectively. The cost-effectiveness of CO₂ mitigation scenarios range from 14.9 to 41.8 US\$/tCO₂e.

1. Introduction

Electricity is a basic need in modern societies. Global electricity demand in the period of 2002–2012 increased 3.6% annually, exceeding the annual population growth for the same period [1]. Yet, 1.3 billion people worldwide still do not have access to electricity, making the provision of universal access to electricity an important

development objective [2]. According to the International Energy Agency (IEA), electricity demand will grow more than 70% by 2040 compared to 2013 [3]. Yet, fossil fuel based electricity production causes greenhouse gas emission (GHG) measured in CO₂ equivalents. Since 2000 GHG emissions have increased 2.4% a year [3] reaching 49 GtCO₂e in 2010, out of which 25% came from electricity and heat production [2].

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The Paris Agreement requires all parties to communicate their Intended Nationally Determined Contributions (INDCs). Around 99% of the communicated INDCs cover the energy sector [4]. Accordingly, they need to incorporate their Paris target into national energy planning. Developing countries, in particular, need to align the Paris Agreement target with their vital national goals of nationwide electrification. This article addresses the question of if and how developing countries may satisfy the growing electricity demand while still meeting climate mitigation targets. We focus on Indonesia; a country with a stable growing GDP and a population of 261 million, spread across more than 13,000 islands. Aligned with the 2015 Paris Agreement, Indonesia aims to reduce its GHGs by up to 29% against business as usual, by 2030. Over and above this, an additional 12% reduction is intended with international cooperation¹. In the meantime, 7.7 million Indonesian households still do not have access to electricity². This article considers both objectives of electrification and climate change mitigation in the simulation of capacity expansion in the largest power system in Indonesia. We focus on the Java-Bali interconnected power system, which generated 74% of the national electrical energy in 2015.

This article analyses various scenarios of future power generation in the Java-Bali power system between 2016 through to 2030. We employ the Long-range Energy Alternatives Planning System (LEAP) and a unique dataset from the national electricity company (PLN). LEAP is selected over other software tools to suit our modelling needs, through a systematic screening process. Despite the fact that LEAP is actively used – in the 85 UNFCCC country report [5] and in more than 70 peer-reviewed journal papers [6] – publications explicitly discussing the LEAP model validation are limited. In this study, we first setup the Indonesian LEAP model and run it from the base year 2005 through to 2015. Then, we validate the model results against the historical data of the national capacity addition, electricity production and CO₂ emission over the period of 2006 through to 2015. Secondly, we develop scenarios for future power generation in the Java-Bali power system and analyse the changes in resource utilization and technology deployment that respond to the Paris pledge with eleven power generation alternatives, namely: ultra supercritical coal (USC coal), natural gas combined cycle (NGCC), natural gas open cycle (NGOC), hydro, mini hydro, hydro pumped storage, geothermal, solar photovoltaic (PV), wind power, nuclear and biomass.

The article adds a number of innovative contributions to the body of the energy modelling literature. Firstly, to the best of our knowledge, this article is the first to analyse scenarios of power system expansion, which take into account the energy sector's actual CO₂ mitigation targets associated with the Indonesian pledge to the Paris Agreement. We assess the consequences of the climate mitigation policy on the Indonesian power sector using a validated model and zoom into the level of individual technologies (a bottom-up approach), rather than employing a macro-economic approach. Secondly, we use a unique dataset from the national power company (PLN) that represents historical technical performances of every individual power plant in the Java-Bali power system of 64 plants. Such a dataset enables more accurate settings for some of the crucial LEAP input parameters, including each plant's net capacity and capacity factor³. Thirdly, this article is transparent on the LEAP validation procedure by using 10 years of Indonesian electricity supply and demand data. As such, the article lays out an easy-to-replicate method for assessing power sector pathways with regard to the Paris Agreement in other developing countries.

The remainder of this paper is organised as follows: Section 2 is the

Literature Review; Section 3 presents the methodology and data, including validation of the LEAP model and scenarios development of the Java-Bali power system expansion; Section 4 provides the results of LEAP simulations; and Section 5 concludes the discussion.

2. Literature review

2.1. Overview of the Indonesian power sector

Indonesia is one of the world's fast developing economies, where annual growth has averaged 5.9% from the year 2010 through to 2014⁴. Accordingly, the Indonesian power sector faces fast-growing energy demands. The average growth rate of electricity consumption in that period was 7.8% [8]. Yet, the present electrification ratio⁵ in Indonesia is only 88% [9]. The country's development agenda aims to improve electrification to nearly 100% by 2020⁶. Furthermore, the Government of Indonesia is promoting an average of 5% economic growth per annum to reduce the poverty rate below 4% by 2025⁷. This implies that the demand for electricity in Indonesia will continue to grow in the next decade and is expected to more than double by 2025 [8].

By the end of 2015, the capacity of national power generation had reached 53 GW (GW) while in the same year, the peak demand was recorded at 34 GW [10]. It is pertinent to note that while the physical infrastructure spreads throughout the Indonesian archipelago, most power generation capacity (64%) is situated in the Java and Bali islands. PLN, the national power company, owns 76% of the national power generation capacity; private companies own the rest. Furthermore, the transmission and distribution grids are run solely by PLN.

The Indonesian power sector, including the Java-Bali interconnected power system, is highly dependent on fossil fuels, primarily on coal. In 2015, fossil fuels constituted 90% and 91% of the national and Java-Bali generation mixes, respectively (Fig. 1). As such, the Java-Bali power system is illustrative of the national energy mix. Furthermore, since Java and Bali are the most populated and developed islands in Indonesia, the electricity consumption in these islands continues to increase with an annual average growth of 7.5% between 2010 and 2014 [11]. In 2015, the Java-Bali power system generated 74% of the national electricity production. Consequently, Java-Bali contributes the highest share of power sector GHG emissions into the national balance, when compared to the outer islands. This article focuses entirely on the analysis of the Java-Bali power system since this is representative in terms of demand growth, energy mix and CO₂ emissions, and given our access to high quality data for this system.

Indonesia owns abundant energy resources including oil, coal, natural gas, solar, hydro, and geothermal (Tables 1 and 2). In 2015, the cumulative reserves of the three fossil fuel resources constituted 93 billion ton oil equivalent/toe. Nonetheless, the fossil fuel resources are depleting. Unless new reserves are discovered Indonesian oil are expected to be exhausted in 12 years, natural gas in 33 years, and coal in 82 years [13]. Meanwhile, the potential of renewable energy is huge (Table 2), and yet it is hardly utilised. Out of the 801 GW of the renewable energy potential, only less than 9 GW or around 1% is utilised to date [14]. Thus, a transition to renewable energy technology is not merely a luxury imposed by the Paris Agreement pledge, it is a necessity; this given the growing national energy demand, its implications on the country's development, and the exhaustion of cheap local fossil fuel supplies. Naturally, a timely utilization of the local renewable energy potential for power generation in Indonesia is a matter of a

¹ The Indonesian voluntary pledge is written in the document of Intended Nationally Determined Contribution (INDC) submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in 2015.

² Calculated from Ref. [9].

³ Capacity factor is defined as the ratio of an actual electricity generation over a given period of time to the maximum possible electricity generation over the same period of time [7].

⁴ Calculated from Statistics Indonesia data, <http://www.bps.go.id/>.

⁵ Electrification ratio is defined as the ratio between the number of households with electricity access to the total number of households.

⁶ Stipulated in the National Energy Policy 2014.

⁷ Stipulated in the Intended Nationally Determined Contribution Republic of Indonesia, 2015.

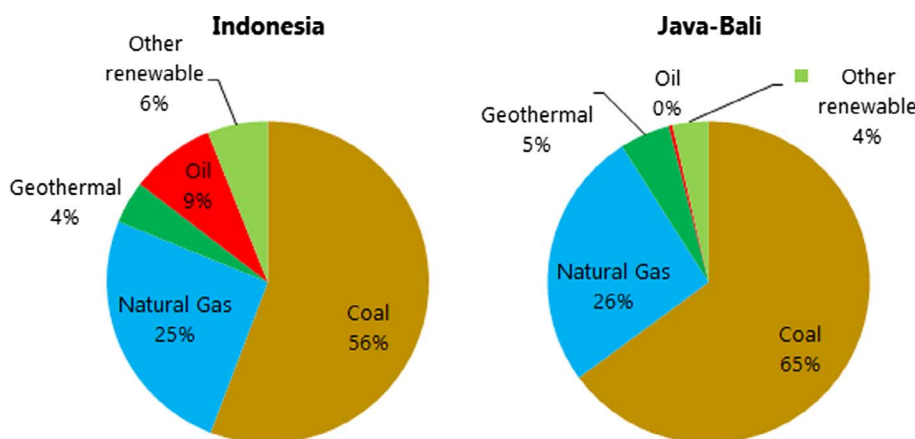


Fig. 1. The National and Java-Bali power generation mixes in 2015 [12]. [This data include both PLN and IPP productions].

Table 1
Primary energy resources in Indonesia [15].

Primary energy	Reserve	
	Total Indonesia	Java, Madura and Bali islands
Coal	126.6 billion ton (88.6 billion toe)	0.98 billion ton
Natural gas	151.3 TCF (3.9 billion toe)	Data not available
Oil	3.6 billion barrels (0.5 billion toe)	Data not available

Table 2
Renewable energy potential.

Renewable	Potential ^a in Gigawatt	
	Total Indonesia	Java- Bali
Hydro	75	4.2
Hydro pumped storage	4.3 ^b	3.9 ^b
Mini hydro	19.4	2.9
Geothermal	17.5 [*]	6.8 [*]
Biomass	30	7.4
Solar	207.9	33.1
Wind	60.6	24.1

Source:
^a Ref. [13].
^b Ref. [16].
^{*} Excluding the speculative and hypothetical potential.

careful assessment of costs and prospective benefits. To increase the chances of acceptance and implementation of the Paris target, and to decrease the likelihood of a fossil fuel technology lock-in for the upcoming power system expansion in Indonesia, quantitative scenarios of power system developments that accommodate renewable energy are needed.

2.2. Paris agreement and de-carbonization of the power sector

A number of studies discuss de-carbonization strategies in developing countries and the implications in response to their commitment to the Paris Agreement. Grande-Acosta and Islas-Samperio [17] present an alternative scenario for the Mexican power sector, by assessing various mitigation options both on the demand and supply sides. Their study concluded that the alternative scenario assures the Mexican compliance with the Paris Agreement. However, the scenario entails an additional investment of 2 billion US\$/year over the analysis period. Likewise, Dalla Longa and van der Zwaan [18] analysed the role of low carbon technologies in achieving Kenya’s CO₂ mitigation target under

the Paris Agreement. One conclusion of this study is that the deployment of these technologies raises the energy system costs in 2050 ranging from 0.5% to 2% of the country’s GDP. Kim et al. [19] investigated the impact of the South Korean’s INDC on the power system and electricity market in Korea. The study revealed that the implementation of INDC causes an increase in the electricity price by as much as 8.6 won/kWh. Another study of the South Korean power sector [20] assessed the impact of national policies triggered by the Paris Agreement – i.e. renewable portfolio standard and feed-in-tariff – on the diffusion of renewable electricity. The study confirmed that the policies indeed influence renewable electricity diffusion. Meanwhile, in response to the Paris Agreement, China needs to radically de-carbonize its electricity sector, which will create unintended consequences, such as the disturbance in stability and integrity due to intermittent renewable energy generation [21]. Thus, Guo et al. [21] present analysis of de-carbonization of the Chinese power sector taking into consideration these temporal variations. This study found that the inclusion of temporal variations resulted in a significant difference in terms of installed capacity and load factors when compared to the standard model. Wan et al. [22] assesses the impacts of Paris climate targets on water consumptions of power sector in major emitting economies, which include Brazil, China, India, US, EU and Russia. The study discovered that the fulfilment of long-term climate targets will increase water consumption of power sector, when compared to the business as usual pathways, particularly in the case of China and India.

Studies on de-carbonization of the Indonesian power sector are available in the literature. Marpaung et al. [23] used a decomposition model to examine two factors (i.e. the technological substitution effect and the demand side effect) that affect CO₂ emissions by considering an influence of external costs on the development of the Indonesian power sector during the period of 2006–2025. This study concluded that increasing external cost at a high level allowed for technological substitution, which led to CO₂ emissions reduction by up to 82.5%. Meanwhile, at the low to medium external costs, CO₂ emission reduction was mainly due to demand side effect. Shrestha and Marpaung [24] used an input-output decomposition approach to analyse factors that affect economy-wide change in CO₂, SO₂ and NO_x emissions in the case when the Indonesian power sector employs integrated resource planning (IRP) approach, rather than traditional supply-based electricity planning (TEP). The IRP approach resulted in CO₂, SO₂ and NO_x emission reductions of 431, 1.6 and 1.3 million tons, respectively, during 2006–2025, as compared to that under TEP approach. Rachmatullah et al. [25] used the scenario-planning method to devise a long-term electricity supply plan (1998–2013) of the Java-Bali power system, which included analysis on CO₂ emissions. This study showed that 15% CO₂ emission could be reduced at an abatement cost of around US\$2.8–4.0 per ton. Wijaya and Limmeechokchai [26] introduced low carbon society actions into the long-term Indonesian

power system expansion planning (2007–2025), using the LEAP model. This study concluded that the low carbon society actions reduced external cost by 2 billion US\$ as compared to the conventional electricity expansion planning. Purwanto et al. [27] developed a multi-objective optimization model of long-term electricity generation planning (2011–2050) to assess the economic, environmental, and energy resources adequacy. That study revealed an electricity system scenario with high orientation on environmental protection became the most sustainable scenario, yet lacked in term of Reserve to Production Ratio (R/P) and cost-related indicators. Kumar [28] analysed the effects of different renewable energy policy scenarios on CO₂ emissions reduction, employing the LEAP model. The results showed that utilization of the Indonesian renewable energy potentials reduced up to 81% of CO₂ emissions when compared to the baseline scenario. These studies analysed long-term power system expansions and their associated CO₂ emissions. However, they did not set specific targets on CO₂ mitigation as a constraint in the simulations of future power generation.

A few studies set a specific target for CO₂ emission in the Indonesian power sector, and simulated patterns of power supply to meet the targets set. Marpaung et al. [29] developed a general equilibrium model i.e. Asia-Pacific Integrated Model (AIM)/Enduse for Indonesia and analysed the effects of introducing a CO₂ emission targets on the technology mix of the Indonesian power sector during 2013–2035. The study concluded that the deployment of carbon capture and storage (CCS), biomass, and wind power technologies, contributed significantly to achieving the targets. Das and Ahlgren [30] analysed CO₂ reduction targets scenario for the long-term Indonesian power system expansion planning (2004–2030) using the MARKAL model. The results showed that constraints on CO₂ emission invoked changes in technology mixes. Similarly, Stich and Hamacher [31] applied different levels of CO₂ emission reduction targets to the optimized power supply in Indonesia. Their results demonstrated that the CO₂ emission constraints boosted geothermal power expansion to replace the coal-fired power generation. Finally, Siagian et al. [32] used AIM to simulate energy sector development over the period 2005–2030 under CO₂ constraints stipulated in a draft policy document. Their study indicated carbon prices of US\$16 and US\$63 (2005)/tCO₂ under 17.5% and 32.7% CO₂ reduction scenarios, respectively. Neither of these studies is associated with the prevailing Indonesian policy as stipulated in the final Nationally Determined Contribution (NDC) as submitted to UNFCCC after the Paris Agreement came into force. Our study fills this gap by incorporating the actual energy sector's mitigation targets – i.e. 11% CO₂ reduction on its own effort and 14% CO₂ with international support – into power capacity expansion. Hence, our analysis can be used as a reference when formulating the legal framework for curbing CO₂ emissions in the power sector.

3. Methodology and data

3.1. Review of available models and selection of an appropriate model

Rigorous models for analysing long-term planning are necessary to support any optimal allocation of investments. While numerous energy system models are developed and used worldwide [33], not all are suitable for performing technological, economical, and environmental analysis of the national power sector. Consequently, this calls for the careful selection of a model. Urban et al. [34] provided a comparison of 12 models in terms of their suitability for applications in developing countries. The study argued that the characteristics of an energy system in developing countries differed from those of developed countries. They found that the energy-related characteristics of developing countries, such as supply shortages, urbanization and low electrification rate, were neglected in many models. Bhattacharyya [35] provided an assessment of 12 energy system models suitable for analysing energy, environment, and climate change policies in developing countries. This study suggested that the accounting-type models were more

relevant for developing countries because of their ability to capture rural-urban differences, traditional and modern energy technologies as well as non-monetary transactions. Connolly et al. [6] reviewed energy system models to identify ones suitable to analyse the integration of 100% renewable energy into various energy systems. The paper presented a brief summary of 37 models. Most included the power sector in their analysis. However, they varied significantly in their purpose. We filtered the models to identify those that are open access and suitable for analysing the technical, economical, and environmental parameters of a long-term power system expansion in a developing country. The detailed inventory of models and screening criteria are presented in Appendix A (Table A.1).

This screening produced a shortlist of 30 models as being potentially suitable for our analysis (Appendix A, Table A.2). We chose the LEAP model for a number of reasons. Firstly, it can accommodate various characteristics essential for an energy sector analysis in developing countries [34]. Secondly, LEAP is freely accessible to students, as well as non-profit and academic institutions in developing countries. This increases the chances of reproducing and further developing this analysis beyond the efforts in the current article, as and when new data and policy considerations become available. In addition, LEAP is very user-friendly and provides open-access online support for its users. Finally, LEAP is considered as a popular energy model, as it has been used in 190 countries and hosts more than 32,900 members in its online platform [5]. It makes results comparable across countries, which is especially relevant when major international agreements such as the Paris accord are considered.

Indeed, LEAP has been used in many studies for analysing CO₂ mitigation in the power sector worldwide. The LEAP model is employed to explore various scenarios of the energy system development in Taiwan [36], China [37], Iran [38], Panama [39], Maharashtra, India [40], Pakistan [41], and Africa [42]. LEAP has also been actively applied to study the energy and CO₂ impacts of a power system expansion with a special focus on a particular energy source such as landfill gas in Korea [43], nuclear in Korea and Japan [44,45] and renewable in Southeast Asia [28]. None of these studies combined the accounting and optimization settings in LEAP for the analysis. Yet, the features provide for different types of analysis, which is essential for a choice of a robust policy. On the one hand, the accounting method in LEAP can be used to represent future power systems based on various policy scenarios, enabling the comparison of energy, environmental and economic impacts of various energy policies. This method provides answers for a “what if” type of analysis. On the other hand, the optimization method in LEAP optimizes investment decisions and, thus, provides a picture of what could be the optimal pathway of power system development. In this study, we employed both accounting and optimization methods from LEAP to analyse scenarios of CO₂ mitigation in the Java-Bali power system.

3.2. Validation of the Indonesian LEAP model

3.2.1. Model setup

We started by setting up a LEAP model of the Indonesian power system from the base year of 2005–2015. The structure of the model is shown in Fig. 2. LEAP consists of three modules namely: demand, transformation and resources modules. Electricity generation belongs to the transformation module. The electricity generation module in LEAP simulates electricity supply to satisfy the given demand, based on various input parameters (Table 3). The model outputs consist of added capacities, a composition of technologies, electricity generation, GHG emissions, and costs.

We initialized LEAP with 2005 data and simulated the expansion of PLN's power generation capacity from 2006 to 2015. According to the PLN statistics, coal steam turbine (CST), natural gas combined cycle (NGCC), natural gas open cycle, diesel generator, hydro, geothermal and solar power were the main technologies employed during this time.

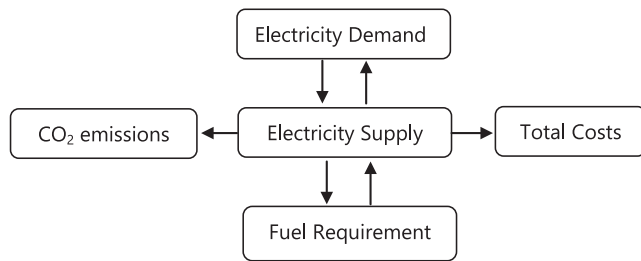


Fig. 2. The LEAP model structure.

CST and NGCC expanded significantly during this period, i.e. 72% and 18% of the total capacity addition respectively, leaving the remaining 10% of the capacity addition shared between the rest. Thus, the Indonesian LEAP model endogenously simulates CST and NGCC for capacity expansion, while the other technologies are exogenously added.

Table 3 lists the type of model outputs, as well as the employed input data and the data used for validation of the Indonesian LEAP model. The input data for electricity demand is the actual values of the national electricity consumption during 2005–2015. The power system characteristics such as transmission losses and a load shape as well as technologies characteristics are based on the actual values. Meanwhile, the data used for validation of the model results consists of historical electricity generation, historical capacity expansion of each technology, and historical fuel consumptions. Appendix B presents detailed information regarding parameters for the Indonesian LEAP model validation.

The simulation of electricity generation in LEAP consists of two steps. First, LEAP calculates the capacity expansion required to satisfy the demand and the capacity reserve of the power system. The outputs of this calculation are the capacity added each year and the composition of technology (capacity mix). Second, LEAP dispatches electricity from each process in accordance with the annual demand and the load curve. The output of the second step is the annual electricity production from each process, which later determines the annual GHG emissions.

As discussed above, LEAP has two different settings for simulating electricity generation: accounting settings and optimization settings (Table 4). We compare the simulation results from both of these settings with the actual data of the year 2005–2015 to validate the model performance.

3.2.2. Validation results

The results show that LEAP calculated the total capacity added (Step 1 in LEAP) during the period of 2006–2015 accurately (Table 5). LEAP slightly underestimated the added capacity, when compared to the empirical data under both the accounting and optimization settings: by

Table 3
Input-output parameters in the Indonesian LEAP model and data used for validation.

Input parameter	Model outputs	Data used for validation
– Electricity demand (2005–2015) ^a	– Electricity generation (2005–2015)	– Historical electricity generation (2005–2015) ^a
– Transmission & distribution losses (2005–2015) ^a	– Capacity added (2006–2015)	– Historical capacity addition (2006–2015) ^b
– Reserve margin (2005–2015) ^b	– Technology mix of the capacity added	– Actual technology mix of the capacity added ^a
– Load shape ^c	– Fuel requirement	– Fuel consumption ^a
– Power generation capacities ^a	– CO ₂ emissions	– CO ₂ emissions ^f
– Fuel efficiency ^d		
– Investment cost of each technology ^e		
– Operation cost of each technology ^a		

Source:

^a PLN Statistics 2005–2015.
^b Reserve margins are calculated based on peak load and capacity data in the PLN Statistics 2005–2015.
^c Load shape is drawn based on hourly load data during 2015 recorded by PLN dispatcher unit (P2B).
^d Fuel efficiency of each technology is calculated based on actual electricity production and fuel consumption recorded in the PLN statistics 2005.
^e Electricity Supply Business Plan 2006–2015/RUPTL.
^f Historical CO₂ emissions are calculated using IPCC Tier 1 emission factor.

just 0.7% and 1.8%, respectively. As a result, in our case the accounting setting was found to be more reliable i.e. 99.3% accuracy, when compared to the 89.2% accuracy of the optimization settings.

The model results also accurately represented the actual technology mix of the capacity added over the period 2006–2015 with 100% and 99% accuracy in accounting and optimization settings, respectively. The optimization setting results, which accurately reproduced the technology mix, indicate that the Indonesian power sector development during this period was based on least-cost principal. This is in line with the PLN’s capacity expansion policy as stipulated in the Electricity Supply Business Plan (RUPTL) [46].

The results of total electricity production – Step 2 in LEAP – and GHG emissions are shown in Table 6. The calibrated LEAP model calculated precisely the total electricity production in the period between 2006 and 2015, both in the accounting and optimization settings i.e. 100% and 99.93% accuracy, respectively. Meanwhile, the model overestimated the CO₂ emissions by 2.6% and 2.5% in the accounting and optimization settings, respectively.

Based on these results, we concluded that LEAP calculations were accurate. However, as is the case with any other energy model, the simulations in LEAP depend on input data and assumptions. Hence, it may generate uncertainty in outcomes when long run future perspectives are taken.

3.3. Future scenarios development

The validation phase (Section 3.2) indicated that the LEAP model estimates of the capacity added, technology mix, cumulative electricity production and CO₂ emissions were reliable. We moved to a scenario analysis of possible future developments of the Java-Bali power system. We developed four scenarios of a capacity expansion for the Java-Bali power system. The scenarios were developed based on the changes in LEAP’s assumptions on the choice of a power generation technology and/or a type of energy source. All scenarios aimed to reduce CO₂ emissions in line with the Indonesian pledge to the Paris Agreement.

The first scenario (REF) represents the continuity of the present trend that sets the benchmark. The second and third scenarios – namely: NGS and REN, respectively – follow The National Energy Policy 2014 (NEP) [47]. NEP aimed to increase the use of natural gas and new and renewable energy to attain minimum 22% and 23% shares, respectively, in the national energy mix by 2025. The new and renewable energy target in NEP includes nuclear. Nonetheless, NEP emphasizes that nuclear is the least preferable option. These three scenarios use the accounting settings in LEAP, which enable the analysis of different paths of the future of power supply, based on different policy assumptions considering the realistic constrains Indonesia currently faces. Meanwhile, the fourth scenario (OPT) uses the optimization setting of LEAP to find the least-cost solution for the capacity expansion and

Table 4
Two alternative simulation settings in LEAP.

	Accounting setting	Optimization setting
Step 1: Capacity addition	LEAP controls when to add new supply capacity based on annual electricity demand.	LEAP controls the type of new supply capacity to be added and when it will be added based on annual demand and cost optimization.
Step 2: Electricity dispatch from each type of power supply	LEAP controls the dispatch of electricity from each process based on a user-defined merit order.	Driven by cost optimization, LEAP controls the dispatch of electricity from each process.

Table 5
A comparison of the estimated national capacity added in 2006–2015 with the actual data.

	Empirical data	LEAP estimates			
		Accounting settings	Difference	Optimization settings	Difference
Cumulative capacity added 2006–2015	15.6 GW	15.5 GW	-0.7%	15.4 GW	-1.8%
<i>Technology mix of the added capacities</i>					
Coal	81%	81%	0%	80%	-1%
Natural gas	19%	19%	0%	20%	+1%

electricity dispatch. As such, this scenario does not account for the realistic policy constrains per se but rather serves as a normative benchmark from the cost minimization perspective.

The objective of all scenarios is to meet the growing electricity demand of the future while fulfilling the Indonesian commitment under the Paris Agreement. According to the Indonesian First Nationally Determined Contribution (NDC) document [48], Indonesia is committed to reduce 29% of GHG emissions by 2030, compared to the business as usual scenario. A more ambitious target is set at 41% reduction, subject to the availability of financial support from developed countries. Given the 29% and 41% targets, 11% and 14%, respectively, should be reduced by the energy sector alone. These targets are lower when compared to those of the forestry sector, which are 17% (own effort) and 23% (with international support). This is expected as the forestry sector⁸ contributed 51% of total emissions over the period of 2000–2012, while the energy sector contributed 32% over the same period [49]. With no mitigation policy, the energy sector alone is expected to produce up to 1669 million tCO₂e of GHG emissions in 2030 [48]. This consists of emissions from the power, transportation and other energy sub-sectors. Yet, the NDC document does not specify the CO₂ emission baseline for the power sector alone. Hence, for all practical purposes, we assume that the power sector contributes proportional to the national energy sector target. Accordingly, we assume that the Java-Bali power system should reduce its emissions at least at the same pace as agreed upon at the national level. Thus, 11% and 14% by 2030 are our targets for setting up the scenarios.

To quantify possible pathways of reaching these competing targets, we specify the four scenarios of development of the Java-Bali power system in the period 2016–2030 as follows:

Reference scenario (REF): According to our data, in the year 2015, coal-fired power plants were the dominant technology in the Java-Bali power system. Net capacity of the coal power plants was 17.3 MW or 55% of the total capacity in the Java-Bali power system. The natural gas power constituted 34% of the total capacity, while renewable capacity share was only 11%, which consisted of geothermal (8%) and hydro (3%). Biomass, wind power, solar photovoltaic (PV) and nuclear technologies were not present in the 2015 capacity mix. The REF scenario assumes that the power system expands with the 2015 technology mix, which persists until the end of the modelling horizon. This pathway does not incorporate any CO₂ mitigation policies and continues the historical capacity expansion

policy based merely on cost-optimization [11]. The abundance of coal resources in Indonesia and the low cost of coal technology leads to the lock-in with the coal technology along the REF pathway.

Natural gas scenario (NGS): This scenario assumes an increasing rate of the natural gas power plant's development. This is in line with the NEP 2014, which aims to increase the share of natural gas in the national energy mix. The substitution of coal by 'cleaner' natural gas is expected to reduce GHG emissions, due to the lower emission factor of natural gas when compared to that of coal. We ran this scenario in two versions. The NGS1 scenario aimed to achieve the 11% CO₂ reduction target compared to the REF scenario that relies entirely on own efforts, without any support from international partners. The NGS2 scenario assumes international partners provide support to Indonesia, and this curbs the CO₂ emissions by 14% compared to the REF scenario.

Renewable energy scenario (REN): This scenario assumes an increase in the development of renewable energy, which includes geothermal, hydro, biomass, wind and solar PV. In this scenario, the power system expansion maximizes utilization of the renewable energy potential of the Java-Bali islands to achieve the Paris target. This scenario is in line with the NEP 2014, which aims to increase the use of new and renewable energy in the national energy mix. The REN1 scenario aims for the 11% CO₂ reduction target, and REN2 scenario for the 14% CO₂ reduction target.

Optimization scenario (OPT): This scenario uses LEAP's optimization settings to obtain the least-cost solution for the Java-Bali power capacity expansion, while satisfying both the increasing demand and CO₂ reduction targets. The least-cost solution in LEAP is defined as the power system with the lowest total net present value of costs of the system over the entire time horizon. In the OPT scenario, all technologies that are included in the REF, NGS, and REN scenarios are considered for capacity expansion. The OPT1 and OPT2 scenarios assume 11% and 14% CO₂ reduction targets, correspondingly.

3.4. Input data

The data source and methodology to calculate the parameters of the Java-Bali power system are provided in Table 7. Rather than relying on the generic LEAP default values, we use national and regional data. Thus, most of the input parameters were collected from governmental reports and the national electricity company, PLN. Since PLN is the sole owner and operator of the Java-Bali power transmission and distribution network, it also records and manages electricity dispatch from Independent Power Producers (IPPs).

⁸ Including land use change.

Table 6
A comparison of the estimated national electricity production and GHG emissions with the actual data.

	Empirical data	LEAP estimate			
		Accounting setting	Difference	Optimization setting	Difference
Cumulative electricity production 2006–2015	1398 TWh	1398 TWh	0%	1397 TWh	0.07%
Cumulative GHG emissions 2006–2015	1030 MtCO ₂ e	1057 MtCO ₂ e	+ 2.62%	1056 MtCO ₂ e	+ 2.53%

Table 7
Summary of model input parameter.

Input data	Value	Source
Annual demand growth 2016–2030	6.8–7.5%	Refers to the RUPTL estimates [16]
Transmission & distribution losses	7.9–8.5%	Refers to the draft RUKN estimates [50]
System load shape	See Appendix C Fig. C1	Based on hourly demand data recorded by P2B [51]
Reserve margin [*]	35%	Refers to the RUKN criteria [50]
Capacities of existing power plants	See Appendix C	Net capacity recorded by P2B [56]
Merit order in the accounting setting:		Maintained according to the P2B dispatch order [56]
- Baseload power plants	Coal, geothermal	
- Intermediate/peak load power plants	Natural gas, hydro	
Environmental parameter	Per technology	The IPCC Tier 1 default emission factors, embedded in the technology database of LEAP [5]
Discount rate	12%	Discount rate used by PLN [57]

**In the accounting setting of LEAP, merit order is the order in which a power plant will be dispatched [5].

* Reserve margin is the percentage of reserve capacity relative to the capacity needed to meet the normal peak demand.

The demand projection for the year 2016–2025 is calculated based on the estimated demand growth in RUPTL [16]. Meanwhile, the demand projection for the remaining years (2026–2030) was calculated assuming that demand for electricity continues to grow at the same rate as the estimated growth in the year 2026 i.e. 7%. It is assumed that transmission losses will gradually decrease from 8.6% in the year 2015 to 7.9% in the year 2030 [50]. The energy load shape is drawn in the LEAP model based on the historical hourly load data collected from the Java Bali dispatcher unit (P2B), as shown in Appendix C, Fig. C.1 [51]. The planning reserve margin was set at 35% in accordance with the criteria in the National Electricity General Plan 2015–2014 (RUKN) [50].

One limitation in LEAP is that the model does not provide for the expansion of transmission and distribution lines. Hence, this study assumes that there are no constraints in the electricity networks, meaning that electricity supply can be transmitted at any time to any load station. Consequently, calculation of costs in this study does not include costs for transmission lines.

The calculation of electricity generation in LEAP depends on the input of the projected electricity demand in the demand module (Fig. 2). After that, the electricity generation module in LEAP assigns technologies to satisfy the electricity demand. The type of power generation technologies for the capacity expansion includes CST, NGCC, natural gas open cycle, diesel generator, hydroelectric (small and large-scale), geothermal, biomass, wind turbine, solar PV and nuclear. The existing coal power plants in Java-Bali use conventional technologies, which have relatively lower efficiencies compared to the supercritical (SC) and ultra-supercritical (USC) technologies. According to RUPTL, to improve efficiency and reduce CO₂ emissions, the future coal power plant's development in the Java-Bali power system would only consider SC and USC technologies [11]. Thus, this study only considered USC coal technology for the new future coal capacity addition. To date, there are no nuclear power plants in Indonesia. However, in the future, development of a large-scale national nuclear energy supply is possible as indicated in NEP. Yet, NEP considers nuclear as the last option after maximizing the use of renewable energy sources.

Technology data of the existing power plants in the Java-Bali system were collected from PLN. These data include the power generating capacity of each technology, planned retirement, heat rate, historical production and capacity factor. The accuracy of the existing power

plant data is essential to ensure a reliable base year data, which was used as reference for developing power expansion scenarios. The capacities of existing power plants in the Java-Bali power system are presented in Appendix C, Table C.1.

Technology data for future capacity expansion were retrieved from various studies, as shown in Table 8. The costs characteristic of power generation technologies refers to the cost assumptions of the world energy outlook (WEO) model [52]. Costs data that was not presented in the WEO model 2016 were taken from the Indonesian Energy Outlook (IEO) 2016 [53], which relied on data from the International Energy Agency (IEA) database of the WEO 2015. These parameters were assumed to be constant throughout the entire simulation. Fuel costs of coal and natural gas were taken from the PLN Statistics 2015 [10], while nuclear fuel cost was taken from the EIA study [54] and biomass fuel cost was sourced from ASEAN Energy Centre (ACE) study [55].

The calculation of the resources/fuel requirements in LEAP depends on the outputs of the electricity generation module. LEAP allocates resources needed for the electricity generation in accordance with the fuel efficiency of each technology. It is essential to take into consideration the availability of the energy resources for the Indonesian LEAP model, particularly with regard to renewable energy, as it can only be utilized locally. Hence, the expansion of renewable power generation in this study takes into account the potential of renewable energy in the JB islands. For practical reasons, we assume that the publicly available data for the Indonesian renewable energy potential (Table 1) is accurate and the total renewable potential can be exploited over the time horizon of this study. Furthermore, we assumed that Indonesian natural gas reserves could be utilized for power generation without any constraint.

4. Balancing the Paris target and the Java-Bali capacity expansion: LEAP results

4.1. Reference scenario (REF)

In the REF scenario, the total capacity added during 2016–2030 is 63.8 GW. Thus the power generation capacity in 2030 reaches 94.2 MW (Fig. 3a). The capacity mix in 2030 is equivalent with the base year, when coal, natural gas, and renewables constituted 55%, 33% and 12% of the total capacity, respectively. A small portion of oil capacity (0.3%)

Table 8
Characteristics of technologies in the Java-Bali LEAP model.

Technology	Lifetime (years) ^a	Efficiency (%) ^b	Availability (%) ^c	Capacity credit (%) ^{e, d}	Capital cost (2015 US\$/kW) ^b	Fixed OM cost (2015 US\$/kW) ^b	Variable OM cost (2015 US\$/MWh) ^c	Fuel cost ^e (2015 US\$)
USC coal	30	44	80	100	1867	64	3.8	51.8 US\$/ton
Natural gas combined cycle	25	57	80	100	817	24	3.8	7.6 US\$/MMBTU
Natural gas open cycle	25	38	80	100	439	21	3.8	7.6 US\$/MMBTU
Hydro	35	100	41	51	2200	56	3.8	–
Mini hydro	35	100	46	58	3350	67	3.8	–
Hydro-pumped storage	35	95 ^c	20	25	1050 ^c	54 ^c	3.8	–
Geothermal	20	10	80	100	2675	53	0.7	–
Solar PV	20	100	17	22	1953	20	0.4	–
Wind power	20	100	28	35	1756	44	0.8	–
Nuclear	40 ^f	33	85 ^g	100	3967	164	8.6 ^g	9.33 US\$/MWh ^g
Biomass	20 ^h	35	80	100	2228	78	6.5	11.67 US\$/ton ⁱ

* Capacity credit in LEAP is defined as the fraction of the rated capacity considered firm for calculating the reserve margin [5].

^a IEA [58].

^b OECD/IEA [52].

^c DEN [53].

^d Calculated based on the ratio of availability of the intermittent plant to the availability of a standard thermal plant [5].

^e PLN [10].

^f Rothwell and Rust [59].

^g IEA and NEA [54].

^h Ref. [60].

ⁱ ACE [55].

remains present in the capacity mix.

In 2030, the corresponding electricity production from coal increases from 108 TWh in 2015 to 350 TWh. Coal contributes 75% of the electricity production in 2030 while natural gas and renewable energy contribute 18% and 7% respectively (Fig. 3b).

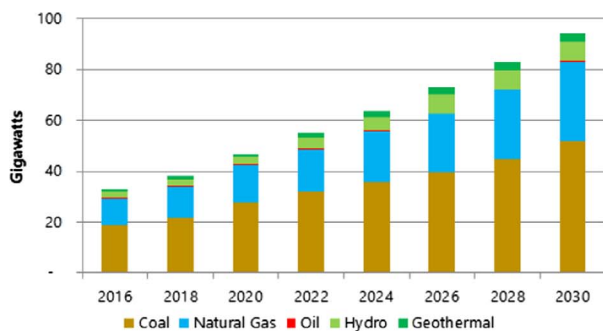
The resulting CO₂ emissions in 2030 are 339 million tCO₂e or nearly three-fold of the emissions in the base year. These are our baseline for the CO₂ reduction in the mitigation scenarios (NGS, REN, and OPT). Table 9 shows the CO₂ emissions baseline and reduction targets.

4.2. Natural gas scenario (NGS)

The results of the LEAP simulations for the NGS scenario indicate that switching from coal to natural gas alone can already deliver both 11% and 14% CO₂ reduction targets. This switching requires around 0.3 billion toe of natural gas, which is equivalent to 8% of the Indonesian natural gas reserve.

4.2.1. NGS1 scenario aiming at the 11% CO₂ reduction

In the NGS1 scenario, the natural gas capacity in 2030 expands up to 45.7 GW; nearly a fivefold increase of capacity over 2015. It is a 15% increase of the gas share in the capacity mix as compared to the REF



(a) Power generation capacity 2015-2030

Table 9
Emission reduction targets against the REF scenario.

CO ₂ emissions level in 2030 (REF), million tCO ₂ e	CO ₂ reduction target in 2030 (%)	CO ₂ emission reduction in 2030, million tCO ₂ e
339	11%	37.3
339	14%	47.5

scenario (Fig. 4a). Consequently, the coal capacity share decreases from 52% in the REF scenario down to 39% in the NGS1 scenario. Compared to the REF scenario, the corresponding electricity production from natural gas increases significantly. In the NGS1 scenario, natural gas constitutes 37% of the electricity generation in 2030; more than two-fold compared to its share in the REF scenario. Accordingly, coal power generation decreases from 75% in the REF scenario to 56% in the NGS1 scenario.

4.2.2. NGS2 scenario aiming at the 14% CO₂ reduction

In order to reduce the CO₂ emissions by 14% against the REF scenario, further expansion of the natural gas capacity is required. Our

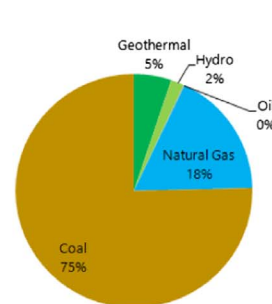


Fig. 3. Reference scenario.

(b) Electricity generation mix in 2030

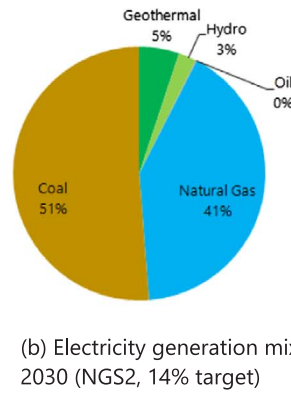
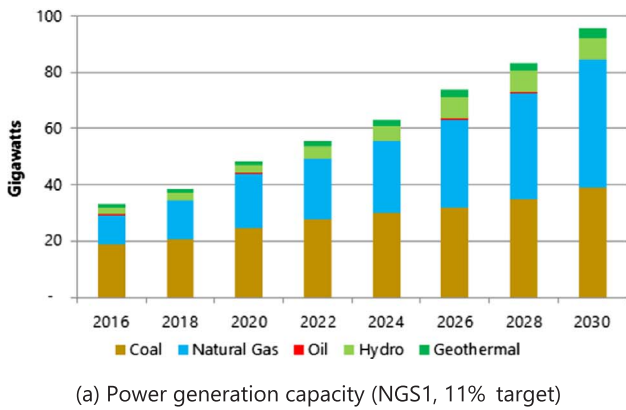


Fig. 4. Natural gas scenario.

results indicate that it takes an additional 1.8 GW of the natural gas capacity when compared to the NGS1 scenario. Consequently, the share of natural gas power generation in 2030 increases up to 41%, which is 4% higher than the NGS1 scenario (Fig. 4b). Meanwhile, the coal capacity share declines to 38%, leading to a reduced share of the coal power generation of 51% compared to 75% in REF.

4.3. Renewable energy scenario (REN)

In the REN scenario, the capacity of renewable energy increases significantly in order to attain both 11% and 14% CO₂ reduction targets. Accordingly, the corresponding electricity production from renewable energy also grows in both REN1 and REN2 scenarios (Fig. 5). The deployment of renewable energy in REN refers to RUPTL, which stipulates the plan to maximize the utilization of hydro and geothermal potentials, and to add up to 5 GW and 2.5 GW of solar PV and wind power capacities respectively by 2025 [16]. Meanwhile, no specific target is set for biomass, although the document mentions the plan to add 0.1 GW of municipal waste power plants. In this study, we assumed that 1 GW and 2 GW of biomass capacities are added in REN1 and REN2 scenarios, respectively, out of the total 7.4 GW biomass potentials of the Java-Bali islands.

4.3.1. REN1 scenario aiming at the 11% CO₂ reduction

The renewable capacity in the REN1 scenario adds up to 21.7 GW or two-fold of the renewable capacity addition present in the REF scenario. Renewables now account for 22% of the total power generation capacity in 2030, split between hydro (9.6%), geothermal (6.8%), wind power (1.5%), biomass (1%), and solar PV (3%). Consequently, the

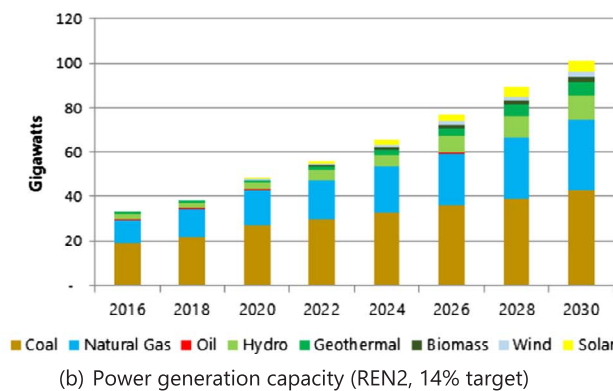
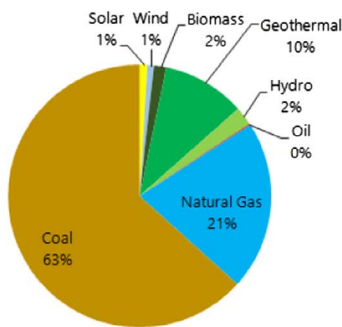


Fig. 5. Renewable energy scenario.

share of renewable electricity generation increases up to 16% of the total power generation in 2030, which is two times higher than in REF.

4.3.2. REN2 scenario aiming at the 14% CO₂ reduction

To accomplish the 14% CO₂ reduction target, 4.8 GW of renewables are added on top of their capacity in REN1. In 2030 the renewables capacity reaches 26.5 GW constituting 26% of the total power generation capacity. The share of each renewable is now slightly increased compared to REN1 i.e. hydro 10.2%, geothermal 6.6%, wind 2.5%, biomass 2% and solar PV 4.9%. Meanwhile, the share of renewable electricity generation adds up to 19% as compared to 7% in REF.

4.4. Optimization scenario (OPT)

Based on the simulation results of the OPT scenario, the least cost options for meeting the Paris target is to expand both the renewable energy and natural gas capacities. Accordingly, coal capacity is slightly decreased (Fig. 6).

4.4.1. OPT1 scenario aiming at the 11% CO₂ reduction

In the OPT1 scenario, the renewables capacity addition accounts for 12.8 GW (Fig. 6a). This a significant increase from 7.2 GW in REF and consists of hydro (5.1 GW), geothermal (5.5 GW) and biomass (2.2 GW). Wind, solar PV and nuclear do not appear in this capacity mix, implying that they are less competitive compared to the other technologies. If there are significant changes in, for example, PV technology, it may change in the future. The natural gas capacity increases 8% from 31.3 GW in REF to 33.7 GW in the OPT1 scenario. Meanwhile, the coal capacity decreases 2% from 51.8 GW in REF down to 50.8 GW

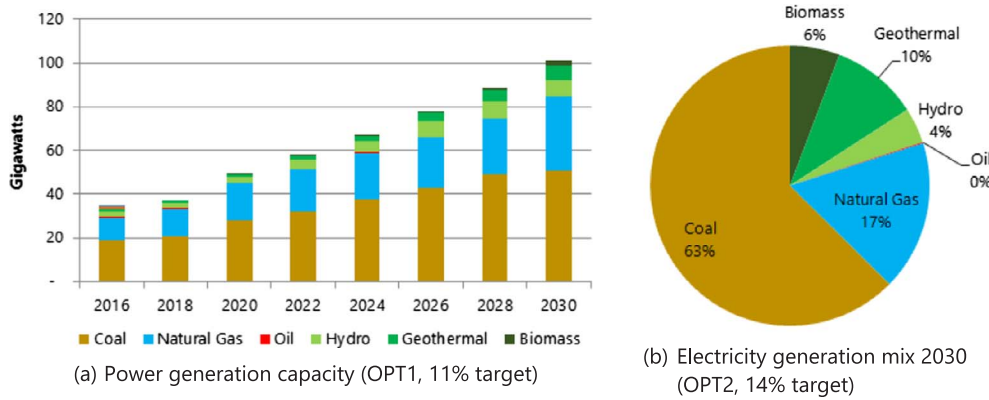


Fig. 6. Electricity generation in the OPT scenario.

Table 10
Total costs of power system expansion in different scenarios.

Scenarios	CO ₂ reduction against REF in 2030 (million tCO ₂ e)	Total costs (billion USD)	CO ₂ mitigation costs (billion USD)	Cost-effectiveness of CO ₂ mitigation (USD/tCO ₂ e)
Reference (REF)	0	49.8		
Natural gas 1 (NGS1)	38.2	50.7	0.85	22.2
Natural gas 2 (NGS2)	47.1	51.2	1.37	29.1
Renewable energy 1 (REN1)	38.9	51.0	1.18	30.4
Renewable energy 2 (REN2)	47.7	51.8	1.99	41.8
Optimization 1 (OPT1)	37.9	50.4	0.57	14.9
Optimization 2 (OPT2)	47.8	50.7	0.85	17.7

in the OPT1 scenario.

Thus, the OPT1 cost-efficient electricity generation mix in 2030 consists of coal (66%), natural gas (17%), and renewables (17%). Despite its slightly decreased capacity, the production share of coal remains the highest due to its dominance in 2015 (65% of the total production) and the cheap price of coal resources. This indicates a high chance of lock-in with the coal technology infrastructure, if no other criteria, other than cost minimization, are at play.

4.4.2. OPT2 scenario aiming at the 14% CO₂ reduction

The results of the OPT2 scenario show that 3% supplementary CO₂ reduction can be attained through an addition of 0.5 GW and 1.6 GW of natural gas and biomass capacities respectively as substitutes of coal. These produce an electricity generation mix comprising of coal (63%), renewables (20%), and natural gas (17%), in year 2030 (Fig. 6b).

Biomass capacity in OPT is higher than that in REN because this scenario does not necessarily follow the national power supply plan, which focuses on hydro, geothermal, solar PV and wind. Instead, it opts for the least-cost power supply options from among all available options. This indicates that electricity generation from biomass is cheaper than that from solar PV and wind.

While the renewable capacity in the OPT scenarios are smaller than in REN, the electricity generation from renewables in these scenarios are higher. This is because the renewable technologies in the OPT scenarios (geothermal, hydro and biomass) have relatively higher capacity factors than solar PV and wind power, which constitute the major capacity share in the REN scenario. Meanwhile, the natural gas share in the 2030's electricity generation mix of OPT is lower, i.e. 17% instead of 18% in REF. This is due to the CO₂ constraints set in OPT, which allows more renewable power generation as a substitute for some portions of both coal and natural gas.

4.5. CO₂ mitigation costs

In LEAP, the total costs of power system expansion consist of capital costs, fixed operation and maintenance (OM) costs, variable OM costs, and fuel costs throughout the planning horizon. Table 10 shows the total costs for all our scenarios. The costs of CO₂ mitigation are the difference between the total costs of the Java-Bali power system expansion in the REF and in each mitigation scenario. The total cost of the Java-Bali power system expansion in the REF scenario is equal to 0.1% of the cumulative national GDP during the study period⁹. The model projects increased costs are 1.1%, 1.7% and 2.7% in OPT1, NGS1 and REN1 scenarios, respectively, in order to reduce 11% of the CO₂ emissions compared to REF. Furthermore, reducing 14% of emissions leads to the increased costs of 1.7%, 2.4% and 4% in OPT2, NGS2 and REN2 scenarios, respectively, which can be covered by climate finance as mandated by the Paris Agreement. The CO₂ mitigation costs in each scenario range from 0.002% to 0.004% of the total GDP.

The REN scenarios impose the highest total costs among the three sets of mitigation scenarios, while the OPT scenarios offer the lowest. Hence, the most cost-effective CO₂ mitigation scenario is the OPT scenario, followed by the NGS scenario. The optimization method in the OPT scenario ensures the lowest total costs of the power system expansion in meeting the mitigation target. The OPT covers technology of the REF with an addition of biomass technology. These results suggest that the deployment of biomass has the lowest cost impact in achieving both 11% and 14% CO₂ reduction targets, compared to deploying wind, solar and nuclear technologies. However, the optimal mix can be sensitive to the input assumptions such as the relative performance of different technologies or future costs. Due to the lack of projections regarding changes in costs of different technologies, we keep it aside as

⁹ Assuming annual GDP growth of 4.5%.

a subject for future research.

Table 10 also shows the cost-effectiveness of the CO₂ mitigation scenarios. For the 11% CO₂ reduction target, the abatement cost are 14.9, 22.2 and 30.4 US\$/tCO₂e in OPT1, NGS1 and REN1, respectively. Meanwhile, for the 14% CO₂ reduction target, the abatement cost are 17.7, 29.1 and 41.8 US\$/tCO₂e in OPT2, NGS2 and REN2, respectively. A sensitivity analysis for different discount rates was performed to understand their impacts on cost effectiveness, and particularly for the OPT scenario on technology mix. The results are presented in Appendix D.

Providing reliable and affordable electrical energy for the entire population is a vital development goal of the Indonesian Government. The electricity tariff is determined by the government and subsidies are allocated for low-income households to ensure electrical energy is affordable for all people. In 2017 alone, the electricity subsidy accounts for 3% of the Government's revenue [61,62]. Thus, it is paramount to maintain low electricity production costs. As such, the Indonesian power sector development follows the 'least costs' principal, with electricity supply options chosen based on the lowest cost [11]. Any additional cost, such as the cost incurred due to the compliance with the Paris Agreement, will increase the electricity production costs, which eventually can increase the price paid by consumer and the size of the government subsidy.

5. Conclusions

Assuring electricity access for the entire population is still a vital national development goal for many developing countries, including the Indonesian Government. Likewise, climate change mitigation and adaptation policies are also essential for developing countries, due to their vulnerability to climate change impacts. Our research analysed plausible trade-offs between electrification and climate goals in the Java-Bali islands. Our focus was on alternatives that could allow Indonesia to satisfy the future electricity demand, while also meeting its Paris climate targets. We chose the LEAP model to perform the analysis after a systematic review of different models (Appendix A). At first, the model was carefully validated using the actual data of the Indonesian power system in the period 2005–2015. Then, four sets of scenarios of the power system expansion for the period 2016–2030 were developed and analysed. The analysis results obtained can be summarized as follows:

- (1) In the reference case where the power capacity expansion of the Java Bali power system continues as per the present pattern (REF scenario), the fossil-fuel power plants remain dominant until the end of the study period. As a result, the CO₂ emissions in 2030 are nearly triple those witnessed in 2015.
- (2) In the context of the Java-Bali power system, the energy sector target associated with the Paris pledge – 11% or 14% reduction – is achievable under the proposed capacity expansion scenarios. The NGS scenario results in a large addition of natural gas capacity i.e.

36.5 GW and 38.5 GW under the NGS1 and NGS2 scenarios, respectively. This indicates that the sole substitution of coal by natural gas can reduce emissions by 11% and 14% from REF. REN scenarios lead to addition of the renewable capacity of 18.1 GW and 22.9 GW under the REN1 and REN2 scenarios, respectively. The OPT scenarios that focus on cost-minimization result in expansions of both renewable energy and natural gas capacities.

- (3) The total cost of the Java-Bali power system expansion under the REF scenario is equal to 0.1% of the Indonesian GDP during the analysis period. Any of the CO₂ mitigation efforts aligned with the Java-Bali capacity expansion increases the costs from 1% to 4% of the REF cost. The cost-effectiveness of CO₂ mitigation scenarios is 14.9–41.8 US\$/t CO₂e, respectively.

Overall, our study indicates that, in the contexts of the Java-Bali power system, the Paris target can be met solely by fuel switching from coal to natural gas. Though gas is a cleaner fuel, this strategy would not use the Indonesian potential of its renewable energy. The national electrification goals can also be achieved, without breaking the Paris Agreement, by escalating the development of renewable energy. However, the most cost-effective measure is by increasing renewable energy development in combination with an expansion of natural gas power generation capacity. As far as costs are concerned, our results are aligned with other studies regarding the implication of the Paris Agreement on power sector in developing countries, for example, the case of Korea [19] and Kenya [18].

Our results demonstrate that any effort to comply with the Paris climate target will impact the electricity generation costs. Currently, there is no regulation in place in Indonesia to limit CO₂ emissions from the power sector. Development of such a policy needs to consider the cost implications for the power generation companies, as these costs, eventually, are bound to pass onto the consumers or have to be covered by governmentals subsidies.

We have incorporated the Indonesian Paris targets into the power capacity expansion. However, there is a number of important methodological issues that should be incorporated in any future work. In particular, these types of assessments would benefit greatly by taking into consideration climate change impacts on the future power system, and possible adaptation strategies in the power sector. It is also vital to account for the evolution of energy technology – as most technologies in time become more cost effective [63] – and analyse their impact on the robustness of the power system expansion scenarios within the Paris Agreement constraints.

Acknowledgements

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Appendix A. Systematic screening of energy models

See Tables A.1 and A.2.

Table A.1
Inventory of energy system models.

No.	Model	Suitability Criteria					
		Able to simulate capacity expansion of a large power system	Wide options of power generation technologies	Calculate costs	Simulation period of min 10 years	Calculate CO ₂ emissions	
1	AEOLIUS [6,64]	No	Yes	Yes	No	Yes	
2	BALMOREL [6,65]	Yes	Yes	Yes	Yes	Yes	
3	BHCP screening tool [6,66]	No	No	Yes	No	Yes	
4	Compare options for sustainable energy/COMPOSE [6,67]	No	Yes	Yes	Yes	Yes	
5	E4cast [6,68]	Yes	Yes	Yes	Yes	Yes	
6	Electricity Market Complex Adaptive Systems/EMCAS [69]	No	Yes	Yes	No	No	
7	Early Market Introduction of New Energy Technologies/EMINEN [6,70]	Yes	Yes	Yes	No	Yes	
8	EF1's Multi-Area Powermarket Simulator/EMPS [6,71]	Yes	Yes	Yes	Yes	Yes	
9	EnergyPLAN [72]	Yes	Yes	Yes	No	Yes	
10	EnergyPRO [6,73]	No	Yes	Yes	Yes	Yes	
11	Energy and Power Evaluation Program/ENPEP-BALANCE [6,74]	Yes	Yes	Yes	Yes	Yes	
12	Generation and Transmission Maximisation Tool/GTMax [6,75]	No	Yes	Yes	Yes	No	
13	H2RES [6,76]	No	Yes	Yes	Yes	Yes	
14	HOMER [6,77]	No	Yes	Yes	No	Yes	
15	Hydrogen Energy Models/HYDROGEMS [6,78]	No	Yes	Yes	No	Not clear ^a	
16	IKARUS [6,79]	Yes	Yes	Yes	Yes	Yes	
17	International Network for Sustainable Energy/INFORSE [6]	Yes	Yes	Yes	Yes	Yes	
19	Long-range Energy Alternative Planning System/LEAP [5]	Yes	Yes	Yes	Yes	Yes	
20	MARKet Allocation model (MARKAL)/The integrated MARKAL-EFOM System/TIMES [80]	Yes	Yes	Yes	Yes	Yes	
21	Model for Energy Supply Strategy Alternatives and their General Environmental impact/MESSAGE [6,81]	Yes	Yes	Yes	Yes	Yes	
22	Mini Climate Assessment Model (MiniCAM)/Global Change Assessment Model/GCAM [82]	Yes	Yes	Yes	Yes	Yes	
23	National Energy Modelling System/NEMS [83]	Yes	Yes	Yes	Yes	Yes	
24	Oak Ridge Competitive Electricity Dispatch/ORCED [84]	Yes	Yes	Yes	Yes	Yes	
25	Programme-package for Emission Reduction Strategies in Energy Use and Supply-Certificate Trading/PERSEUS [64]	Yes	Yes	Yes	Yes	Yes	
26	PRIMES [85]	Yes	Yes	Yes	Yes	Yes	
27	ProdRisk [6]	No	No	Yes	Yes	Not clear ^a	
28	RAMSES [6]	Yes	Yes	Yes	Yes	Yes	
29	Renewable Energy Technology Screening Model/RETScreen [6]	No	Yes	Yes	Yes	Yes	
30	Simulation of Renewable Energy Networks/SimREN [86]	Yes	Yes	Yes	Yes	Not clear ^a	
31	SIVAEL [6]	No	No	Yes	No	Yes	
32	Sustainable Technology Research and Energy Analysis Model/ STREAM [87]	Yes	Yes	Yes	Yes	Yes	
33	TRANSYS16 [88]	No	No	Not clear ^a	Yes	Not clear ^a (continued on next page)	

Table A.1 (continued)

No.	Model	Suitability Criteria	Wide options of power generation technologies	Calculate costs	Simulation period of min 10 years	Calculate CO ₂ emissions
34	UniSyD3.0 [6]	Able to simulate capacity expansion of a large power system	Yes	Yes	Yes	Yes
35	Wien Automatic System Planning Package/WASP [89]		Yes	Yes	Yes	Yes
36	WILMAR Planning Tool [90]		No	Yes	No	Yes
37	Regional Energy Scenario Generator/RESGEN [91]		Yes	Yes	Yes	No
38	Energy Flow Optimisation Model/EFOM [92]		Yes	Yes	Yes	No
39	Prospective outlook on long-term energy systems/POLES [93]		Yes	Yes	Yes	Yes
40	World Energy Model/WEM [52]		Yes	Yes	Yes	Yes
41	System for the analysis of global energy markets/SAGE [94]		Yes	Yes	Yes	Yes
42	Electricity Generation Expansion Analysis System/EGEAS [95]		Yes	Yes	Yes	Yes
43	Asia-Pacific Integrated Model/AIM [96]		Yes	Yes	Yes	Yes
44	Atmospheric Stabilization Framework/ASF [97]		Yes	Yes	Yes	Yes
45	TARGETS-IMAGE Energy Regional Model/IMAGE-TIMER [98]		Yes	Yes	Yes	Yes
46	Multiregional Approach for Resource and Industry Allocation/MARIA [97]		Yes	Yes	Yes	Yes
47	PowerPlan [99]		Yes	Yes	Yes	Yes
48	Second Generation Model (SGM)/Phoenix [100]		Yes	Yes	Yes	Yes

^a Unclear due to insufficient information.

Table A.2
Accessibility of the suitable models.

No	Tools	Accessibility	Link to free download
1.	Balmorel	Free ^a	http://www.balmorel.com/index.php/downloadmodel
2.	E4cast	Commercial	
3.	EMPS	Commercial	
4.	ENPEP-BALANCE	Free	Email to ceesa@anl.gov
5.	H2RES	Internal use only	
6.	IKARUS	Commercial	
7.	INFORSE	Free to INFORSE members and cooperating European networks	
8.	LEAP	Free ^b	https://www.energycommunity.org/default.asp?action=download
9.	MARKAL/TIMES	Commercial	
10.	Mesap Planet	Commercial	
11.	MESSAGE	Free ^c	
12.	MiniCAM/ GCAM	Free ^a	http://www.globalchange.umd.edu/gcam/download/
13.	NEMS	The model is free, but users must purchase the simulator	https://www.eia.gov/bookshelf/models2001/NationalEnergy.html
14.	ORCED	Used to be free to download	
15.	PERSEUS	Commercial	
16.	PRIMES	Commercial	
17.	SimREN	Commercial	
18.	STREAM	Free	http://streammodel.org/downloads.html
19.	UniSyD3.0	Contact: Prof. Jonathan Leaver: jleaver@unitec.ac.nz	
20.	WASP	Free IAEA member states	
21.	POLES	Commercial	
22.	WEM	Internal use	
23.	SAGE	Model source codes are available ^a	http://www.globaloilwatch.com/reports/mdr-system-analysis-global-energy-markets-eia-082003.pdf
24.	EGEAS	Commercial	
25.	AIM	Free ^a	http://www.iam.nies.go.jp/aim/data_tools/index.html
26.	ASF	Internal use	
27.	IMAGE/TIMER	Contact: image-info@pbl.nl	
28.	MARIA	Internal use	
29.	PowerPlan	Commercial	
30.	SGM/Phoenix	Model source codes are available ^a	http://www.globalchange.umd.edu/data/models/phx_documentation_August_2011.pdf

^a The program is written in GAMS modelling language, which is a commercial software.

^b Free for students and non-profit institutions in developing countries.

^c Free for academic purposes and the International Atomic Energy Agency (IAEA) member states.

Appendix B. Input data for the LEAP Indonesian model 2005–2015

See Tables B.1 and B.2.

Table B.1
Summary of model input parameters for the LEAP Indonesian model 2005–2015.

Data input	Value	Sources
Annual electricity demand 2005–2015	2005: 107,032 GWh 2015: 202,846 GWh	PLN statistics 2005–2015
Transmission & distribution losses	9.7–11.6%	PLN statistics 2005–2015
System load shape	–	P2B
Planning reserve margin	9–35%	Calculated based on historical peak load and capacity data
Capacities of existing power plants	Total capacity 2005: 22.2 GW 2015: 39.9 GW	PLN statistics 2005–2015
Merit order in the accounting setting:		Maintained according to the P2B dispatch order
Baseload power plants	CST, solar PV, geothermal	
Intermediate load power plants	NGCC, hydro	
Peak load power plants	NGOC, DG	
Capacity factor	CST: 65%, NGCC: 50%	Calculated based on data from PLN Statistics 2005–2015
Environmental parameters	–	The IPCC Tier 1 default emission factors, embedded in the technology database of LEAP
Lifetime of technologies	20–40 years	IEA [58]
Discount rate	12%	Refers to discount rate used by PLN

Note: NGOC: natural gas open cycle; DG: diesel generator.

Table B.2
Cost data for the capacity addition 2006–2015.

Technologies	Investment Cost ^a (2005 US\$/kW)	Variable OM Costs ^b (2005 US \$/MWh)	Fuel Costs	
			Costs (2005 US \$) ^b	Unit
CST	850	2.2	25.7	Per metric ton of coal
NGCC	550	5.2	2.65	Per MMBTU of natural gas

Sources:

^a RUPTL 2006–2015 [46].

^b PLN Statistics 2005[101]

Appendix C. Input data for Java-Bali power system expansion 2016–2030

See Fig. C.1 and Table C1.

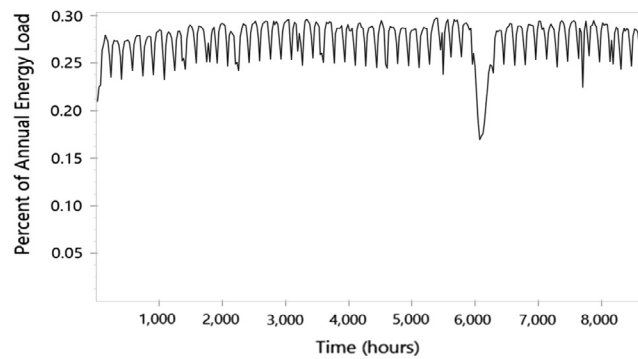


Fig. C.1. Load shape of the Java Bali power system [51].

Table C.1
Power generation capacity of the Java-Bali Power System [56].

Power plants	Net capacity (MW)
Coal steam turbine (CST)	17,339
Natural gas combines cycle (NGCC)	8971
Hydro	2477
Geothermal	1092
Natural gas steam turbine	824
Diesel generator	260
Natural gas open cycle	242
Natural gas engine	200
Total	31,405

Appendix D. Sensitivity analysis

Naturally, a discounting rate impacts any investment decision. Thus, in addition to using the 12% discount rate employed in practice in Indonesia, we perform a sensitivity analysis for 3%, 5%, 8%, 10%, and 14% discount rates. Fig. D.1 presents the cost-effectiveness of CO₂ mitigation at various discount rates. A varying discount rate affects the cost-effectiveness of the NGS scenarios significantly. The NGS scenarios are the second most cost-effective mitigation scenarios at 14% discount rate, but falls into the least cost-effective scenarios at the rest of discount rate values. The REN scenarios are relatively robust to changes in discount rates compared to the other scenarios. However, the cost-effectiveness of REN slightly increases along with the increase of discount rates. The OPT scenarios remains the most cost-effective mitigation scenarios at all discount rate values. The OPT1 scenario yield negative CO₂ abatement costs at all discount rate values except in the case of 10% discount rate. Meanwhile the OPT2 scenario has negative CO₂ abatement costs at 3%, 10% and 14% of discount rate values.

The changes in discount rate do not affect the technology mix of the NGS and REN scenarios since the technology/resource choices in these scenarios are based on policy assumptions. Meanwhile, in the OPT scenarios discount rate assumption has an effect on technology mix since the power system expansion is projected based on costs. The technology mixes of the OPT scenarios at various discount rates are presented in Fig. D.2. The figure shows that natural gas capacity increases along with the increase of discount rate values. Contrarily, the capacity of coal and biomass decreases along with the increase of discount rate values. Furthermore, small amount of wind power (0.5 GW) appears in the capacity mix of the OPT2 scenario at 3% discount rate value.

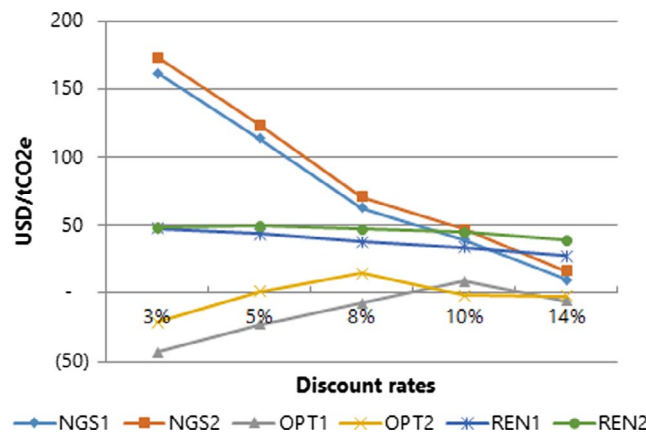


Fig. D.1. Cost-effectiveness of CO₂ mitigation at various discount rates.

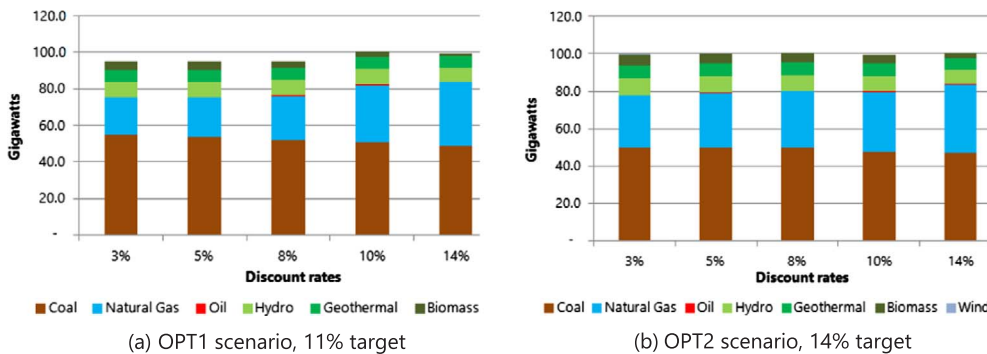


Fig. D.2. Capacity mixes in the Java-Bali power system in 2030, at various discount rates under optimization scenarios.

References

- [1] IEA. Tracking Clean Energy Progress 2015; 2015. Retrieved from France: http://www.iea.org/publications/freepublications/publication/Tracking_Clean_Energy_Progress_2015.pdf.
- [2] IPCC. Climate Change 2014: Mitigation of Climate Change. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Farahani E, Kadner S, Seyboth K, Adler A, Baum I, Brunner S, Eickemeier P, Kriemann B, Savolainen J, Schlömer S, von Stechow C, Zwickel T, Minx JC, editors. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2014.
- [3] IEA. World energy outlook 2015 factsheet; 2015. Retrieved from http://www.worldenergyoutlook.org/media/weowebsite/2015/WEO2015_Factsheets.pdf.
- [4] UNFCCC. Aggregate effect of the intended nationally determined contributions: an update synthesis report by the secretariat; 2016. Retrieved from <http://unfccc.int/resource/docs/2016/cop22/eng/02.pdf>.
- [5] Heaps CG. Long-range Energy Alternatives Planning (LEAP) system. [Software version 2017.0.5]; 2016. Retrieved from <http://www.energycommunity.org>.
- [6] Connolly D, Lund H, Mathiesen BV, Leahy M. A review of computer tools for analysing the integration of renewable energy into various energy systems. Appl Energy 2010;87(4):1059–82. <http://dx.doi.org/10.1016/j.apenergy.2009.09.026>.
- [7] U.S. NRC; 2017. Retrieved from <https://www.nrc.gov/reading-rm/basic-ref/glossary/capacity-factor-net.html>.
- [8] PLN. Electricity Supply Business Plan (RUPTL) 2015–2024; 2015. Retrieved from Jakarta, Indonesia: <http://www.pln.co.id/stakeholder/ruptl>.
- [9] DJK ESDM. Statistik Ketenagalistrikan 2015; 2016. Retrieved from Jakarta, Indonesia: <http://www.djk.esdm.go.id/pdf/Buku%20Statistik%20Ketenagalistrikan%20T.A.%202016.pdf>.
- [10] PLN. PLN statistics 2015 (ISSN: 0852-8179); 2016. Retrieved from Jakarta: <http://www.pln.co.id/stakeholder/laporan-statistik>.
- [11] PLN. Electricity Supply Business Plan (RUPTL) 2016–2025; 2016. Retrieved from <http://www.pln.co.id/stakeholder/ruptl>.
- [12] PLN. PLN management report; 2016. Retrieved from.
- [13] DEN. Sosialisasi Rencana Umum Energi Nasional dalam rangka Penyusunan Rencana Umum Energi Daerah; 2016. Retrieved from <http://www.apbi-icma.org/wp-content/uploads/2016/09/PAPARAN-SOSIALISASI-RUEN-JAKARTA-FINAL.pdf>.

- [14] EBTKE. Isu strategis/permasalahan sub sektor EBTKE. Palembang; 2016.
- [15] MEMR. Handbook of energy and economic statistics of Indonesia 2016 (ISSN 2528-3464); 2016. Retrieved from Jakarta: <https://www.esdm.go.id/assets/media/content/content-handbook-of-energy-economic-statistics-of-indonesia-2016-lvekpnc.pdf>.
- [16] PLN. Electricity supply business plan 2017–2026 (RUPTL); 2017.
- [17] Grande-Acosta G, Islas-Samperio J. Towards a low-carbon electric power system in Mexico. *Energy Sustain Dev* 2017;37:99–109. <http://dx.doi.org/10.1016/j.esd.2017.02.001>.
- [18] Dalla Longa F, van der Zwaan B. Do Kenya's climate change mitigation ambitions necessitate large-scale renewable energy deployment and dedicated low-carbon energy policy? *Renew Energy* 2017;113:1559–68. <http://dx.doi.org/10.1016/j.renene.2017.06.026>.
- [19] Kim K, Park H, Kim H. Real options analysis for renewable energy investment decisions in developing countries. *Renew Sustain Energy Rev* 2017;75:918–26. <http://dx.doi.org/10.1016/j.rser.2016.11.073>.
- [20] Lee C-Y, Huh S-Y. Forecasting the diffusion of renewable electricity considering the impact of policy and oil prices: the case of South Korea. *Appl Energy* 2017;197:29–39. <http://dx.doi.org/10.1016/j.apenergy.2017.03.124>.
- [21] Guo Z, Cheng R, Xu Z, Liu P, Wang Z, Li Z, Jones I, Sun Y. A multi-region load dispatch model for the long-term optimum planning of China's electricity sector. *Appl Energy* 2017;185:556–72. <http://dx.doi.org/10.1016/j.apenergy.2016.10.132>.
- [22] Wan L, Wang C, Cai W. Impacts on water consumption of power sector in major emitting economies under INDC and longer term mitigation scenarios: an input-output based hybrid approach. *Appl Energy* 2016;184:26–39. <http://dx.doi.org/10.1016/j.apenergy.2016.10.013>.
- [23] Marpaung COP, Soebagio A, Shrestha RM. Internalizing external cost in electricity development in Indonesia: a factor decomposition analysis. In: Paper presented at the 2005 IEEE/PES Transmission and Distribution Conference and Exhibition: Asia and Pacific; 2005.
- [24] Shrestha RM, Marpaung COP. Integrated resource planning in the power sector and economy-wide changes in environmental emissions. *Energy Policy* 2006;34(18):3801–11. <http://dx.doi.org/10.1016/j.enpol.2005.08.017>.
- [25] Rachmatullah C, Aye L, Fuller RJ. Scenario planning for the electricity generation in Indonesia. *Energy Policy* 2007;35(4):2352–9. <http://dx.doi.org/10.1016/j.enpol.2006.08.015>.
- [26] Wijaya ME, Limmeechokchai B. The hidden costs of fossil power generation in Indonesia: a reduction approach through low carbon society. *Songklanakarini J Sci Technol* 2010;32(1):81–9.
- [27] Purwanto WW, Pratama YW, Nugroho YS, Warjito, Hertono GF, Hartono D, Deendarlianto, Tezuka T. Multi-objective optimization model for sustainable Indonesian electricity system: analysis of economic, environment, and adequacy of energy sources. *Renew Energy* 2015;81:308–18. <http://dx.doi.org/10.1016/j.renene.2015.03.046>.
- [28] Kumar S. Assessment of renewables for energy security and carbon mitigation in Southeast Asia: the case of Indonesia and Thailand. *Appl Energy* 2016;163:63–70. <http://dx.doi.org/10.1016/j.apenergy.2015.11.019>.
- [29] Marpaung COP, Soebagio A, Shrestha RM. The role of carbon capture and storage and renewable energy for CO2 mitigation in the Indonesian power sector. In: Paper presented at the 8th International Power Engineering Conference, IPEC; 2007.
- [30] Das A, Ahlgren EO. Implications of using clean technologies to power selected ASEAN countries. *Energy Policy* 2010;38(4):1851–71. <http://dx.doi.org/10.1016/j.enpol.2009.11.062>.
- [31] Stich J, Hamacher T. The cost-effectiveness of power generation from geothermal potentials in Indonesia and the Philippines. In: Paper presented at the IEEE PES Innovative Smart Grid Technologies Conference Europe; 2016.
- [32] Siagian UWR, Yuwono BB, Fujimori S, Masui T. Low-carbon energy development in Indonesia in alignment with Intended Nationally Determined Contribution (INDC) by 2030. *Energies* 2017;10(1). <http://dx.doi.org/10.3390/en10010052>.
- [33] Evans J, Hunt LC. *International handbook on the economics of energy*. Northampton, USA: Edward Elgar Publishing Inc; 2009.
- [34] Urban F, Benders RMJ, Moll HC. Modelling energy systems for developing countries. *Energy Policy* 2007;35(6):3473–82. <http://dx.doi.org/10.1016/j.enpol.2006.12.025>.
- [35] Bhattacharyya SC. A review of energy system models. *Int J Energy Sector Manage* 2010;4(4):494–518. <http://dx.doi.org/10.1108/17506221011092742>.
- [36] Yophy H, Jeffrey BY, Chieh-Yu P. The long-term forecast of Taiwan's energy supply and demand: LEAP model application. *Energy Policy* 2011;39(11):6790–803. <http://dx.doi.org/10.1016/j.enpol.2010.10.023>.
- [37] Tao Z, Zhao L, Changxin Z. Research on the prospects of low-carbon economic development in China based on LEAP model. *Energy Procedia* 2011;5:695–9. <http://dx.doi.org/10.1016/j.egypro.2011.03.123>.
- [38] Amirnekoeei K, Ardehali MM, Sadri A. Integrated resource planning for Iran: development of reference energy system, forecast, and long-term energy-environment plan. *Energy* 2012;46(1):374–85. <http://dx.doi.org/10.1016/j.energy.2012.08.013>.
- [39] McPherson M, Karney B. Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. *Energy Policy* 2014;68:146–57. <http://dx.doi.org/10.1016/j.enpol.2014.01.028>.
- [40] Kale RV, Pohekar SD. Electricity demand and supply scenarios for Maharashtra (India) for 2030: an application of long range energy alternatives planning. *Energy Policy* 2014;72:1–13. <http://dx.doi.org/10.1016/j.enpol.2014.05.007>.
- [41] Perwez U, Sohail A, Hassan SF, Zia U. The long-term forecast of Pakistan's electricity supply and demand: an application of long range energy alternatives planning. *Energy* 2015;93:2423–35. <http://dx.doi.org/10.1016/j.energy.2015.10.103>.
- [42] Ouedraogo NS. Modeling sustainable long-term electricity supply-demand in Africa. *Appl Energy* 2017;190:1047–67. <http://dx.doi.org/10.1016/j.apenergy.2016.12.162>.
- [43] Shin H-C, Park J-W, Kim H-S, Shin E-S. Environmental and economic assessment of landfill gas electricity generation in Korea using LEAP model. *Energy Policy* 2005;33(10):1261–70. <http://dx.doi.org/10.1016/j.enpol.2003.12.002>.
- [44] Kim H, Shin E-S, Chung W-J. Energy demand and supply, energy policies, and energy security in the Republic of Korea. *Energy Policy* 2011;39(11):6882–97. <http://dx.doi.org/10.1016/j.enpol.2011.07.056>.
- [45] Takase K, Suzuki T. The Japanese energy sector: current situation, and future paths. *Energy Policy* 2011;39(11):6731–44. <http://dx.doi.org/10.1016/j.enpol.2010.01.036>.
- [46] PLN. Electricity supply business plan 2006–2015; 2005.
- [47] Government of Republic of Indonesia. Government Regulation of Republic of Indonesia No. 79 Year 2014 regarding National Energy Policy; 2014.
- [48] Government of Republic of Indonesia. First nationally determined contribution Republic of Indonesia; 2016. Retrieved from http://www4.unfccc.int/ndcregistry/PublishedDocuments/Indonesia%20First/First%20NDC%20Indonesia_submitted%20to%20UNFCCC%20Set_November%202016.pdf.
- [49] Republic of Indonesia. Indonesia First Biennial Update Report (BUR) under the United Nations Framework Convention on Climate Change; 2015. Retrieved from Jakarta: http://unfccc.int/files/national_reports/non-annex_i_parties/biennial_update_reports/application/pdf/idnbur1.pdf.
- [50] KESDM. Draft Rencana Umum Ketenagalistrikan Nasional 2015–2034; 2015. Retrieved from <http://www.djk.esdm.go.id/pdf/Draft%20RUKN/Draft%20RUKN%202015%20-%20202034.pdf>.
- [51] P2B. Beban Sistem Jawa Bali 2010; 2016.
- [52] OECD/IEA. World energy outlook - world energy model; 2017. Retrieved from <http://www.worldenergyoutlook.org/weomodel/>.
- [53] DEN. Indonesia energy outlook 2016 (ISSN 2503-1597); 2016. Retrieved from <http://www.den.go.id/index.php/publikasi/index/EnergyOutlook>.
- [54] IEA, NEA. Projected costs of generating electricity 2015 Edition; 2015. Retrieved from Paris: <http://www.oecd-nea.org/ndd/pubs/2015/7057-proj-costs-electricity-2015.pdf>.
- [55] ACE. Levelised cost of electricity of selected renewable technologies in the ASEAN member states; 2016. Retrieved from Jakarta: <http://www.aseanenergy.org/resources/publications/asean-resp-levelised-cost-of-electricity-of-selected-renewable-technologies-in-the-asean-member-states/>.
- [56] P2B. Evaluasi Operasi Sistem Jawa Bali 2015. Jakarta: PLN P2B; 2016.
- [57] JICA. Preparatory survey for Indramayu coal-fired power plant project in Indonesia; 2010. Retrieved from.
- [58] IEA. Southeast Asia energy outlook 2015; 2015. Retrieved from France: http://www.iea.org/publications/freepublications/publication/WEO2015_SouthEastAsia.pdf.
- [59] Rothwell G, Rust J. On the optimal lifetime of nuclear power plants. *J Bus Econ Stat* 1997;15(2):195–208. <http://dx.doi.org/10.2307/1392305>.
- [60] IRENA. Renewable energy technologies: cost analysis series; 2012. Retrieved from Abu Dhabi: <http://www.irena.org/Publications/Publications.aspx?mnu=cat&PriMenuID=36&CatID=141&type=all>.
- [61] Gumelar G. Pemerintah Tambah Alokasi Subsidi Listrik 15 Persen di APBNP. CNN Indonesia; 2017. Retrieved from <https://www.cnnindonesia.com/ekonomi/20170614090054-85-221612/pemerintah-tambah-alokasi-subsidi-listrik-15-persen-di-apbnp/>.
- [62] Direktorat Jenderal Anggaran. Informasi APBN 2017; 2017. Retrieved from <http://www.data-apbn.kemenkeu.go.id/Publications/ambilFileDariDisk/22>.
- [63] Rubin ES, Azevedo IML, Jaramillo P, Yeh S. A review of learning rates for electricity supply technologies. *Energy Policy* 2015;86:198–218. <http://dx.doi.org/10.1016/j.enpol.2015.06.011>.
- [64] Rosen J. The future role of renewable energy sources in European electricity supply. A model-based analysis for the EU-15 (Doctor PhD); Retrieved from. Karlsruhe: Universität Karlsruhe (TH); 2007.
- [65] Ravn HF. The Balmorel model: theoretical background; 2001. Retrieved from Denmark: <http://www.balmorel.com>.
- [66] MacDonald M, Pierce E, Fischer S. Using BChP Screener (BChPsc) for Facility Energy Assessments; 2007. Retrieved from <http://eber.ed.orln.gov/bchpsc/class.htm>.
- [67] Blarke MB. The missing link in sustainable energy: Techno-economic consequences of large-scale heat pumps in distributed generation in favour of a domestic integration strategy for sustainable energy (pHD); Retrieved from. Aalborg Universitet; 2008.
- [68] Akmal M, Thorpe S, Dickson A, Burg G, Klijn N. Australian Energy: National and State Projections to 2019–20, ABARE eReport 04.11; 2004. Retrieved from Canberra: <https://www.environment.gov.au/system/files/pages/b26f2202-5c5d-42a0-8486-95b15238bbd7/files/hs31pc12776energy-projections.pdf>.
- [69] North M, Conzelmann G, Koritarov V, Macal C, Thimmapuram P, Veselka T. E-laboratories: agent-based modeling of electricity markets. In: Paper presented at the 2002 American Power Conference; 2002.
- [70] Klemeš J, Bulatov I, Koppejan J. Novel energy saving technologies evaluation tool. *Comp Chem Eng* 2009;33(3):751–8. <http://dx.doi.org/10.1016/j.compchemeng.2008.07.005>.
- [71] Doorman G, Kjölle G, Uhlen K, Huse ES, Flatabó N. Vulnerability of the Nordic power system; 2004. Retrieved from https://ens.dk/sites/ens.dk/files/contents/material/file/vulnerability_nordicpowersystem_0.pdf.
- [72] Lund H. EnergyPLAN advanced energy systems analysis computer model documentation version 11.0. 2013; 2013. Retrieved from <http://www.energyplan.eu/>

- [wp-content/uploads/2013/06/EnergyPLAN-Documentation-Version12.pdf](#).
- [73] EMD International A/S. EnergyPRO; 2017. Retrieved from <http://www.emd.dk/energypro/>.
- [74] CEEESA. Energy and Power Evaluation Program (ENPEP-BALANCE); 2017. Retrieved from <http://ceesa.es.anl.gov/projects/Enpepwin.html>.
- [75] Veselka T. GTMax overview capabilities and features. training on generation and transmission planning and analysis, 5–6 June 2014, ADB Headquarters; 2014.
- [76] Duić N, da Graça Carvalho M. Increasing renewable energy sources in island energy supply: case study Porto Santo. *Renew Sustain Energy Rev* 2004;8(4):383–99. <http://dx.doi.org/10.1016/j.rser.2003.11.004>.
- [77] Lambert T, Gilman P, Lilienthal P. Micropower system modeling with homer Integration of Alternative Sources of Energy. John Wiley & Sons, Inc; 2006. pp. 379–418.
- [78] Ulleberg O, Morkved A. Renewable energy and hydrogen system concepts for remote communities in the West Nordic Region: the Nolsoy case study. *Institute for Energy Technology*; 2008.
- [79] Martinsen D, Krey V, Markewitz P, Vögele S. A time step energy process model for Germany-model structure and results. *Energy Stud Rev* 2006;14(1). <http://dx.doi.org/10.15173/esr.v14i1.480>.
- [80] Loulou R, Labriet M. ETSAP-TIAM: the TIMES integrated assessment model Part I: model structure. *Comput Manage Sci* 2008;5(1):7–40. <http://dx.doi.org/10.1007/s10287-007-0046-z>.
- [81] Tot M IAEA's tool for energy supply system assessment MESSAGE modelling framework; 2012. Retrieved from IRENA-ECREEE Workshop on Energy Planning, Abidjan, Cote D'Ivoire: https://www.irena.org/DocumentDownloads/2012/December/EREP/3_Mario_Tot.pdf.
- [82] The JGCRI GCAM Team. Overview of the Global Change Assessment Model (GCAM); 2016. Retrieved from Joint GCAM Community Modeling Meeting and GTSP Technical Workshop, Maryland, USA: http://www.globalchange.umd.edu/data/annual-meetings/2016/GCAM_overview_combined_2016.pdf.
- [83] EIA U. The National energy modeling system: an overview 2009; 2009. Retrieved from [https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581\(2009\).pdf](https://www.eia.gov/outlooks/aeo/nems/overview/pdf/0581(2009).pdf).
- [84] Hadley SW. The Oak Ridge Competitive Electricity Dispatch (ORCED) model; 2008. Retrieved from <http://info.ornl.gov/sites/publications/files/Pub9472.pdf>.
- [85] Mantzos L, Capros P. The PRIMES version 2 energy system model: design and features; 1998. Retrieved from <http://www.e3mlab.ntua.gr/manuals/PRIMES1d.pdf>.
- [86] Lehmann H. Energy-rich Japan; 2003. Retrieved from http://www.energyrichjapan.info/pdf/ERJ_fullreport.pdf.
- [87] Risø D. Danish greenhouse gas reduction scenarios for 2020 and 2050; 2008. Retrieved from http://www.ea-energianalyse.dk/reports/720_Danish_greenhouse_gas_reduction_2020_2050.pdf.
- [88] Solar Energy Laboratory University of Wisconsin-Madison. TRNSYS 17; 2013. Retrieved from <http://sel.me.wisc.edu/trnsys/features/features.html>.
- [89] International Emissions Trading Association. Wien Automatic System Planning (WASP) package: a computer code for power generating system expansion planning version WASP-IV with user interface user's manual. Vienna, Austria: IAEA; 2006. p. 13–150.
- [90] Meibom P. Design of the Wilmar planning tool; 2005. Retrieved from Wilmar Seminar, Brussels: <http://www.wilmar.risoe.dk/Slides%20from%20Wilmar%20seminar/DesignWilmarPlanningTool%20HVL.pdf>.
- [91] Foell W, Amann M, Carmichael G, Chadwick M, Hetteling J-P, Hordijk L, Dianwu Z. RAINS-Asia: an assessment model for air pollution in Asia: final report submitted to the Bank by the Project Team; 1995. Retrieved from <http://www.iiasa.ac.at/~rains/asia1/>.
- [92] De Kruijk H. The Eu energy and environmental model Ecom-env specified in gams: model description and user's guide: Netherlands Energy Research Foundation ECN; 1994.
- [93] Enerdata. POLES: prospective outlook on long-term energy systems; 2012. Retrieved from <http://ledsgp.org/wp-content/uploads/2015/09/Introduction-to-POLES-Enerfuture.pdf>.
- [94] DOE E. Model documentation report: System for the Analysis of Global Energy Markets (SAGE); 2003. Retrieved from.
- [95] Ng WS. Electric power resource planning: EGEAS software overview; 2015. Retrieved from EPRI Program 178b Webcast: http://eea.epri.com/pdf/NG%20Planning_EPRI_EGEAS_Webcast_041615_Final.pdf.
- [96] AIM Project Team. Asia-Pacific integrated model; 2016. Retrieved from http://www-iam.nies.go.jp/aim/about_us/index.html.
- [97] IPCC. Special report on emissions scenarios: a special report of working group III of the Intergovernmental Panel on Climate Change; 2000. Retrieved from <https://www.ipcc.ch/pdf/special-reports/spm/sres-en.pdf>.
- [98] De Vries B, van Vuuren D, Den Elzen M, Janssen M. Targets Image Energy Regional (TIMER) Model, Technical Documentation; 2002. Retrieved from <http://www.pbl.nl/sites/default/files/cms/publicaties/461502024.pdf>.
- [99] Benders R. Interactive simulation of electricity demand and production. (PhD), University of Groningen; 1996. Retrieved from <http://www.rug.nl/research/portal/files/10217917/titlepag.pdf>.
- [100] Wing IS, Daenzer K, Fisher-Vanden K, Calvin K. Phoenix model documentation; 2011. Retrieved from http://www.globalchange.umd.edu/data/models/phx_documentation_august_2011.pdf.
- [101] PLN. PLN Statistics 2005: Corporate Secretary PT PLN (Persero); 2006.