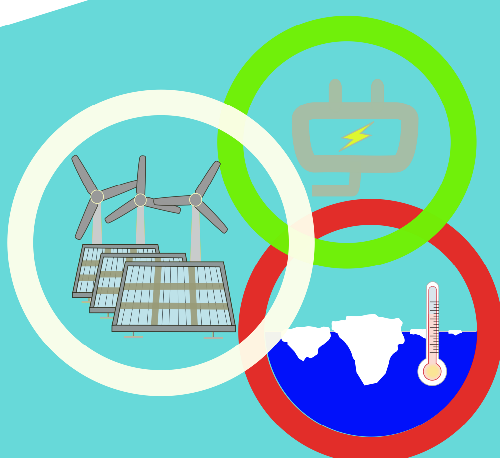
ELECTRICITY & CLIMATE CHANGE

SEEKING FOR THE TRIPLE NEXUS OF ELECTRIFICATION, CLIMATE CHANGE MITIGATION, AND CLIMATE CHANGE ADAPTATION



KAMIA HANDAYANI

Electricity & climate change

Seeking for the triple nexus of electrification, climate change mitigation, and climate change adaptation

DISSERTATION

to obtain
the degree of doctor at the University of Twente,
on the authority of the rector magnificus,
Prof. dr. T.T.M. Palstra,
on account of the decision of the graduation committee,
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by

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born on the 27th of May 1978
In Garut, Indonesia

This dissertation has been approved by

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This book ends my journey as a PhD researcher, but it is certainly not the end of my work on energy and climate change.

Enschede, October 2019

Kamia Handayani

Contents

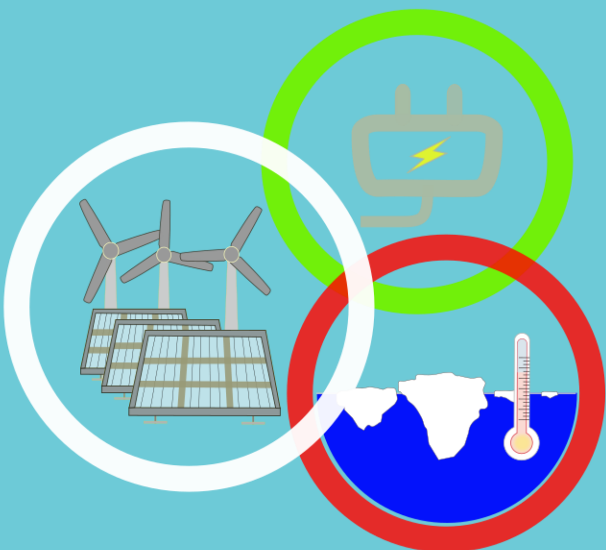
List of Abbreviations

BAU	Business As Usual
BMKG	Badan Meteorologi, Klimatologi dan Geofisika (the Agency for Meteorology, Climatology, and Geophysics)
CFPP	Coal-fired Power Plant
CST	Coal Steam Turbine
IEA	International Energy Agency
ENS	Energy Not Supplied
ETL	Endogenous Technological Learning
GHG	Greenhouse Gas
GWh	Gigawatt-hour
HEPP	Hydroelectric Power Plant
IEO	Indonesia Energy Outlook
INDC	Intended Nationally Determined Contribution
IP	PT Indonesia Power
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
kWh	Kilowatt-hour
LEAP	Long-range Energy Alternatives Planning system
NDC	Nationally Determined Contribution
NEP	National Energy Policy
NGCC	Natural Gas Combined Cycle

NGOC	Natural Gas Open Cycle
NGPP	Natural Gas Power Plant
NRE	New and Renewable Energy
P2B	Pusat Pengatur Beban (Load Control Center)
PJB	PT Pembangkitan Jawa Bali
PLN	Perusahaan Listrik Negara (State Electricity Company)
PV	Photovoltaic
RCP	Representative Concentration Pathway
RUPTL	Rencana Usaha Penyediaan Tenaga Listrik (Electricity Business Supply Plan)
SDGs	Sustainable Development Goals
SEI	Stockholm Environment Institute
T&D	Transmission and Distribution
TWh	Terawatt-hour
TPP	Thermal Power Plant
UNFCCC	United Nations Framework Convention on Climate Change
USC	Ultra-Supercritical
WEAP	Water Evaluation And Planning system
WEO	World Energy Outlook

1

General Introduction



1.1. Background

Electricity is a basic need in the modern world. Economic development and social well-being are possible because of electricity (Ferguson et al., 2000; Fouquet, 2011). Accordingly, the speed of electricity growth is the fastest among other sources of total energy demand (IEA, 2018a). In 2016, the world's electricity consumption doubled that of 1990. However, nearly 1 billion people worldwide today are still without access to electricity (IEA, 2018b). Looking ahead, the International Energy Agency (IEA) estimates a 90% increase in global electricity consumption in 2040 due to electrification. Therefore, the power sector is expected to expand further to satisfy future demand for electricity.

While the increase in electricity demand in advanced economies is expected to be relatively modest, developing economies will share an extensive account of the future demand increase, which will be driven by rapid economic and population growth (IEA, 2018a). For the global South, growth in electricity demand is a crucial prerequisite for the development and satisfaction of the United Nations (UN) Sustainable Development Goals (SDGs). For example, Indonesia, a developing economy with 262 million inhabitants, records an annual economic growth of 5.3% between 2012-2016 (BPS, 2018). In the same period, Indonesia experienced a yearly growth of 6.7% in electricity demand (PLN, 2018). Thus, the country is projected to be the world's fourth-largest economy during the 2030s, owing to an increase in the working-age population, which will reach 68% of the total population by 2030 (OECD, 2018). Consequently, the demand for electricity will continue to grow, making the power sector's infrastructure increasingly vital for enabling socio-economic development and progress on SDGs.

Nonetheless, this paramount role of the power sector in driving the country's development comes at a cost. Electricity generation in Indonesia contributes to 43% of the energy sector emissions and 16% to national greenhouse gas emission (GHG) (Rizaldi Boer et al., 2018), owing to the power sector's reliance on fossil fuels, especially coal. Under the Paris Agreement, the country is embarking on a low-carbon pathway and aims to reduce 29% of its carbon emissions by 2030 (Government of The Republic of Indonesia, 2015a). This goal aligns with Indonesia's ambitious target of increasing the share of new[1] and renewable energy in the national energy mix up to 23% in 2025 and 31% in 2050 (Government of The Republic of Indonesia, 2014). Furthermore, while the power sector infrastructure is increasingly crucial for meeting socio-economic and climate change mitigation goals, at the same time, it is threatened by the adverse impacts of climate change. A United Nations Framework Convention on Climate Change (UNFCCC) report confirms that the global South is to bare the most of the latter (UNFCCC, 2007a).

Extreme weather events and gradual changes in climate variables have implications for the reliability, cost, and environmental impacts of the energy supply worldwide (Schaeffer et al., 2012; Cronin et al., 2018). Climate change impacts are expected throughout the entire power sector value chain, including production, transmission, distribution, and consumption. On the supply side, effects of climate change include changes in water availability and the seasonality of hydropower, alterations in wind speed frequency and distribution, reductions in solar cell efficiency, generation cycle efficiency, and the cooling water availability of thermal power plants, and failures and reductions in the capacity of transmission and distribution lines. On the demand side, climate change alters the balance of heating and demand patterns (Schaeffer et al., 2012; Cronin et al., 2018; Audinet et al., 2014).

Moreover, electricity infrastructures are vulnerable to extreme weather events, which are one of the world's leading causes of power outages. A

[1]New energy refers to energy sources that can be produced using new technology, either originating from renewable energy or non-renewable energy, among others, including nuclear, hydrogen, coal bed methane, liquefied coal, and gasified coal (Government of The Republic of Indonesia, 2014)

World Bank report on resilient infrastructure highlights that natural shocks caused 44% of power outages in the US between 2000 and 2017 and 37% of outages in Europe between 2010 and 2017. Such events cost billions of dollars per year for electric utilities, consumers, and governments. Therefore, natural hazards and climate change are pressing problems that in the coming decades, would involve substantial investments (Nicolas et al., 2019).

Thus, the **grand challenge** for the power sector worldwide and Indonesia, in particular, is to develop in a resilient way under the nexus of three objectives: satisfying fast-rising electricity demand, meeting the Paris Agreement and coping with the impact of climate change. One practical challenge is the substantial investment required to develop clean, reliable, and climate-resilient power systems. Even without climate change considerations, the power sector is already capital-intensive (Bhattacharyya, 2011; Nicolas et al., 2019) and with additional objectives of climate change mitigation and adaptation, much higher investments are expected.

To date, the scientific community has accumulated knowledge to address this societal problem, which is reviewed in Section 1.3. However, first, an overview of the case study is presented in Section 1.2. and then Chapter 1.4 discusses the research gaps in the current literature. Thereafter, Chapter 1.5 highlights the core research goal of the dissertation, together with the guiding research questions for attaining this goal and an overview of the mixed methods used in the dissertation. Finally, this chapter ends with an outline of the structure of the entire doctoral dissertation.

1.2. Case study: The Indonesian power sector

Indonesia is one of the world's fast-developing economies. The Government of Indonesia is promoting an average of 5% economic growth per annum to reduce the poverty rate below 4% by 2025 (Government of The Republic of Indonesia, 2016). Meanwhile, to date, more than 14 million Indonesians do not have electricity access (IEA, 2018b). Moreover, the electricity consumption per capita of Indonesia is relatively low, i.e., 870 kilowatt-hours (kWh) in 2016, which is much lower compared to 3,110 kWh of the world's average per capita consumption in the same year (IEA, 2018c). These statistics imply that the demand for electricity in Indonesia will continue to grow in the next decade.

The structure of Indonesia's power sector is vertically integrated: the state-owned electricity company (PLN) monopolizes the retail electricity sale and is the sole purchaser of electricity produced by independent power producers (IPPs). The PLN solely owns and operates the transmission and distribution (T&D) networks, while the power generation assets are divided between PLN, its subsidiaries, and IPPs.

As an archipelagic nation that has more than 16,000 islands (BIG, 2017a), Indonesia's electricity infrastructures are spread into eight major electricity grids and more than 600 isolated grids distributed throughout the archipelago (PWC, 2017). Thus, it is pertinent to note that while the physical infrastructure spreads throughout the Indonesian archipelago, most of the power generation capacity (65%) is situated in the Java and Bali islands (Table 1.1). These islands are the most populated islands, inhabited by over 148 million people, which comprises 57% of the national population (BPS, 2018).

Table 1.1: Capacities of power generation, transmission, and distribution: the total Indonesia and Java-Bali system (KESDM, 2017; PLN, 2017a)

Assets	**Indonesia**	**Java-Bali**	**Percentage of the Java-Bali capacity**
Generation capacity (MW)	59,656	38,690	65%
Transmission network:			
Transmission lines (kmc)	44,064	22,553	51%
Substation transformer (MVA)	98,899	78,697	80%
Distribution network:			
Distribution lines (kmc)	887,681	466,686	53%
Substation transformer (MVA)	50,100	32,822	65%

Note: MW=megawatt; kmc=kilometer circuit; MVA= megavolt ampere

The Indonesian power sector, including the Java-Bali interconnected power system, is highly dependent on fossil fuels. As a locally extracted and relatively cheap resource, coal became the primary energy source in the country. In 2015, fossil fuels constituted 90% and 91% of the national and Java-Bali power generation mixes, respectively (Fig. 1.1). Therefore, the Java-Bali power system is illustrative of the national electricity mix. Furthermore, since Java and Bali are the most populated and developed islands in Indonesia, electricity consumption on these islands has continued to increase, having an annual average growth of 5.9% between 2012 and 2016 (PLN, 2018). Furthermore, in 2018, the Java-Bali power system served 74% of national electricity consumption (PLN, 2019). Consequently, Java-Bali contributed the highest share to the national balance of power sector's GHG emissions, compared to the outer islands.

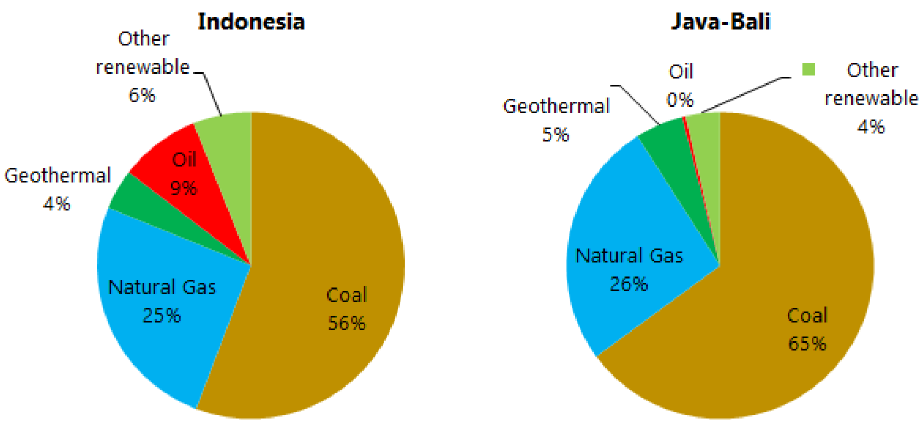


Fig. 1.1: The national and Java-Bali power generation mixes in 2015 (PLN, 2016a). This data includes both PLN and IPP productions.

Indonesia owns abundant energy resources, including oil, coal, natural gas, hydro, geothermal, solar, biomass, and wind resources (Table 1.2 and Table 1.3). In 2015, the cumulative reserves of the three fossil fuel resources constituted 93 billion tons of oil equivalent/toe. Nonetheless, fossil fuel resources are depleting, and unless new reserves are discovered, Indonesian oil is expected to be exhausted in 12 years, natural gas in 33 years, and coal in 82 years (DEN, 2016a).

Table 1.2: Primary energy resources in Indonesia

Primary energy	Reserve	
	Total Indonesia	**Java, Madura, and Bali**
Coal	126.6 billion tons (88.6 billion toe)[a]	19.8 million tons[a]
Natural gas	151.3 TCF (3.9 billion toe)[a]	10.6 TCF[b]
Oil	3.6 billion barrels (0.5 billion toe)[a]	1.2 billion barrels[c]

[a]MEMR (2016), [b]KESDM (2018a), and [c]KESDM (2018b)

Meanwhile, the potential for renewable energy is enormous (Table 1.3); however, this potential is hardly utilized. In 2015, nearly 9 GW, or less than 1% of renewable energy potential, was employed (EBTKE, 2016).

Table 1.3: Renewable energy potential and current practices in Indonesia

Renewable	Potential in Gigawatt (GW)		Renewable deployment by 2015, total Indonesia		Sources
	Total Indonesia	**Java–Bali islands**	**Installed capacity (GW)**	**Renewable utilization (%)**	
Hydro	75	4.2	5.4	7.2%	(DEN, 2016b; ESDM, 2019)
Hydro P/S	4.3	3.9	0	0.0%	(ESDM, 2019; PLN, 2017b)
Mini hydro	19.4	2.9	0.4	2.1%	(DEN, 2016b; ESDM, 2019)
Geothermal	17.5[a]	6.8[a]	1.9	11%	(DEN, 2016b; ESDM, 2019)
Biomass	30	7.4	1.8	6.0%	(DEN, 2016b; ESDM, 2019)
Solar	5,374[b]	2,747[b]	0.06	0.0%	(ESDM, 2019; Kunaifi and Reinders, 2016)
Wind	60.6	24.1	0.0004	0.2%	(DEN, 2016b; ESDM, 2019)

Note: Hydro P/S = hydro pumped storage, [a]excluding speculative and hypothetical potential, [b]in Gigawatt peak

Similar to many other countries, the Indonesian energy sector is required to contribute to the nationally determined contribution (NDC) under the Paris Agreement. This sector is required to cut 11% of national GHG emissions from business as usual (BAU) by 2030. Meanwhile, the power sector in Indonesia is already affected by severe weather events and changes in climate variables. For example, heavy rainfall in March and April of 2010 resulted in excessive water entering reservoirs of the Citarum cascade hydropower on Java island, which caused flooding downstream. In contrast, in 2011, the water level in these reservoirs fell drastically below the normal level, reducing their electricity production (Syariman and Heru, 2011). Likewise, severe weather events adversely affected electricity distribution networks, often causing widespread power cuts (PLN Yogyakarta, 2015).

Considering its vital role for meeting the electrification and Paris Agreement goals, as well as the fact that it is already affected by climate variability, the Indonesian power sector is a vivid example when studying the triple nexus of electrification, climate change mitigation, and climate change adaptation. As such, this doctoral dissertation focuses on the most extensive power system in Indonesia, i.e., the Java-Bali power system, since it is representative of demand growth, energy mix, and CO_2 emissions and given the author's access to high-quality data for this system.

1.3. Analysis of climate change mitigation and adaptation in the power sector: State of the art

1.3.1. Modeling low-carbon pathways in a power system expansion

Making assessments about the future of power systems is not an easy task considering the uncertainty about the future of the power sector, economic situation, and technological progress, among other things. In this context, scenario analysis offers flexibility for the actors to explore a variety of pathways to expand the power system over time, and to evaluate the benefits and consequences of each path.

Energy system models are often utilized to aid in the detailed quantification of scenarios (Hall and Buckley, 2016). They developed during the 1970s and have been used worldwide (Kemfert and Truong, 2009). Varied in purpose (Connolly et al., 2010), each model has a unique paradigm, technique, and solution (Hall and Buckley, 2016). Moreover, energy models can be classified based on the level of aggregation and the theoretical approach being used. This classification divides energy system models into two types: top-down and bottom-up models. While top-down models focus on aggregate linkages between energy, economy, and environment from the context of the national, regional, or global economy as a whole, bottom-up models look at the issues from the perspective of a specific sector, such as electricity generation or transport (Kemfert and Truong, 2009). As such, top-down models focus on market processes rather than technological details, addressing policy concerns related to public finances, economic competitiveness, and employment (van Vuuren et al., 2009). Meanwhile, bottom-up models include a more detailed quantitative description of the technological structure utilized in a sector (Kemfert and Truong, 2009; van Vuuren et al., 2009), thereby modeling the detailed technological complexity of the energy system (Pfenninger et al., 2014).

To assess the trade-offs between electrification and climate change mitigation goals in the power sector, one needs a tool that enables performing a technological, economic, and environmental analysis of the power system expansion. Furthermore, since climate change mitigation in the power sector relies heavily on a variety of energy technologies, it is essential that this tool represents technologies in detail and can incorporate a competition between current and future energy technologies.

Bottom-up energy models, such as the Long-range Energy Alternatives Planning system (LEAP), offer the capability to analyze both a power system expansion and climate policy scenarios, taking into account detailed characteristics of electric power technologies. LEAP, which was developed by the Stockholm Environment Institute (SEI), has been used in 190 countries, becoming the de facto standard tool in developing countries (Heaps, 2017). Its success is accelerated by its free access for developing countries and by the fact that it accommodates various characteristics essential for an energy sector analysis in developing countries, such as electrification and flexible data requirements (Urban et al., 2007).

Numerous studies have applied LEAP when assessing the decarbonization of the power system. For example, McPherson and Karney (2014) explored scenarios for climate change mitigation within Panama's power sector. The study indicates that there is an opportunity for Panama to reduce both greenhouse gas emissions and system generation costs on the condition that there is sufficient private investment. Perwez et al. (2015) included an analysis of a green future scenario for Pakistan's power sector, concluding that a green scenario is more economically efficient in the long run compared to fossil-fuel based scenarios. Samsudin et al. (2016) analyzed the paths of the Malaysian sustainable power sector, showing that sustainable scenarios assure sufficient electricity supply while keeping emissions below the target limit. Ouedraogo (2017) employed LEAP to examine reference and sustainable scenarios for Africa. The study implies that the modification of existing oil and coal plants, as well as the promotion of local renewable resources, allow for fuel diversification in the power sector, which will increase energy security while reducing CO_2 emissions. Similarly, Bhuvanesh et al. (2018) evaluated greenhouse gas mitigation scenarios for Tamil Nadu State, India, and suggested that the adoption of renewable energy sources in the power sector will increase Tamil Nadu's energy independence and also reduce CO_2 emissions.

Worldwide scholars have also applied LEAP to examine the achievement of NDCs in the power sector at a national level, including Mexico's (Grande-Acosta and Islas-Samperio, 2017), Thailand's (Kusumadewi et al., 2017) and Botswana's (Baek et al., 2019) power sectors. Together, these studies indicate that each country's NDC is achievable through the increased deployment of renewable energy, and in the case of Mexico, also through energy-efficient measures. Meanwhile, Kumar and Madlener (2018) go beyond the current NDC by exploring a plausible pathway for the German power sector to achieve 1.5 °C, the Paris Agreement goal. The study reveals that GHG emission comes down to almost zero in 2040, thereby ensuring the achievement of the temperature limit of 1.5 °C. However, in doing so, this will entail high GHG mitigation costs: 194.2 €/t of CO_2e.

A variety of other modeling tools are used in the literature to analyze the power sector pathways towards meeting the Paris Agreement goal. Dalla Longa and van der Zwaan (2017) adopted the TIAM-ECN model to examine the role of low carbon technologies in achieving Kenya's target under the Paris Agreement. Bogdanov et al. (2018) used the LUT Energy System Transition modeling tool to explore the technical feasibility of the Northeast Asia power system for deep decarbonization mandated by the Paris Agreement. Moreover, Haiges et al. (2019) applied TIMES to assess the Malaysian power sector pathways, considering the country's NDC as well as 2050's deep decarbonization. Fortes et al. (2019) employed TIMES_PT to analyze the extension of end-use sector electrification as a cost-effective strategy for deep decarbonization in Portugal. Meanwhile, Gómez-Calvet and Martínez-Duart (2019) proposed a mathematical model based on linear programming to optimize the balance between variable renewable energy sources to be extensively added in the Spanish power sector as a response to the EU's NDC.

Nevertheless, there is still no assessment of the implications of Indonesia's NDC for the power sector, let alone an assessment of the role of technological change in attaining the NDC targets. Furthermore, the link between the Paris Accord's mitigation objectives with the sector's adaptation to climate change has not yet been investigated. Such analyses are critical, as they could provide insights into formulating a policy framework for the power sector to curb CO_2 emissions.

1.3.2. Endogenous technological learning in energy system models

The academic literature agrees that technological changes play a critical role in the historical energy transition, as well as in future scenarios of energy transition (Nakicenovic et al., 2000; Berglund and Söderholm, 2006; IPCC, 2007; Wilson and Grubler, 2011). Even more, technological change is viewed as a critical component of long-term climate change mitigation strategy (Pizer and Popp, 2008). Accordingly, the IPCC Fifth Assessment Report (AR5) highlights the inability of existing technologies to gain a significant reduction needed to meet the IPCC's mitigation scenarios (Pachauri et al., 2014). Thereby, it underlines the importance of institutions and economic incentives to encourage technological change that would lead to reductions in climate change mitigation costs. However, incorporating technological change in energy modeling remains a challenge (Grübler et al., 1999; Frei et al., 2003; Berglund and Söderholm, 2006).

Most energy models treat technological change as exogenous (Grübler et al., 1999; Berglund and Söderholm, 2006; Ma and Nakamori, 2009), integrating this change through numerous assumptions about the costs and performance of future technology. For example, in optimization models, the adoption of low-carbon yet uneconomical technologies can be triggered by creating environmental or capacity constraints, among others (Ma and Nakamori, 2009).

Nonetheless, in reality, technological change is tightly embedded in the developmental trajectory of technology and requires considerable developmental efforts (Berglund and Söderholm, 2006). Accordingly, there is an increasing number of studies that adopt endogenous technological change in energy system models. Technological learning or a learning effect is the most common approach to specifying and incorporating endogenous technological change (Kahouli-Brahmi, 2008). For example, Pratama et al. (2017) applied a multi-objective optimization method that considers technological learning to minimize both the costs of power generation and its corresponding CO_2 emissions for multiple regions in

Indonesia. The study reveals that the incorporation of the learning rate of renewables results in a considerable deployment of renewables to replace coal-based power generation. Meanwhile, Heuberger et al. (2017) integrated endogenous technological learning (ETL) into the ESO-XEL model to simulate the UK's power capacity expansion for the period of 2015-2050 and compared the results between with and without technological learning. The study finds that the consideration of technological learning influences the competitiveness of technology and results in earlier optimal investment. Similarly, Daggash and Mac Dowell (2019) used ESO-XEL, which embodies technological learning to evaluate the UK's power system expansion up to 2100 to address deep decarbonization mandated by the Paris Agreement. The study indicates that the deployment of CCS technology -including bioenergy with carbon capture and storage and direct air capture and storage- is required from 2030 onward to comply with the Paris Agreement goal by the end of the century. Finally, Liu et al. (2018) incorporated technological learning into the TIMES model to evaluate low-carbon technology diffusion in the decarbonization of the Tianjin power sector in China. The study implies that the learning rate is a critical factor in optimization simulation, as it affects the choice of technologies and total system costs.

Despite the increasing recognition of the critical role played by technological learning, there have been no studies incorporating ETL into LEAP, precluding an evaluation of the effects of induced cost reduction on the entire power system.

1.3.3. Adverse impacts of climate change on the power sector

The climate is changing. Even if global GHG emissions are stabilized at 1.5°C above the pre-industrial level, we will still see changes in climate and their impacts, including higher air and seawater temperatures, increased frequency and intensity of heavy precipitation and droughts, sea-level rise, ecosystem damages, and land and forest degradations (IPCC, 2018).

Climate change already affects the entire global economy, including the energy sector. In 2005 alone, extreme climate events accounted for a 13% variation in energy productivity in developing countries (World Bank, 2010). Moreover, future climate change is expected to increase the vulnerability of the power sector, which has attracted the attention of both researchers and practitioners. Financial institutions now include an assessment of climate change impacts on their loan portfolios (Connell et al., 2018; International Finance Corporation, 2012). Moreover, international guidelines for such an assessment are emerging. For example, the World Bank produced a guideline for climate-resilient hydropower, which involved a broad stakeholder engagement during the preparation process (World Bank, 2017). Similarly, the International Standard Organization issued a new international standard, i.e., ISO 14090, to assist companies in assessing climate change impacts and developing effective adaptation plans (Naden, 2019).

To support this societal need of assessing infrastructure resilience, researchers often use simulation models that integrate the projected effects of climate change on future power systems. Naturally, such modeling links to climate change scenarios and their expected impacts resulting from global climate change models. However, climate change may affect various elements of the electricity supply chain and electricity sources differently. Previous studies on this topic have established that climate change reduces the reliability of thermoelectric power plants mainly due to increasing air and cooling water temperatures, and decreasing streamflow (Förster and Lilliestam, 2010; van Vliet et al., 2012; Zheng et al., 2016; Tobin et al., 2018).

Meanwhile, impacts on hydropower are uneven between regions. For example, Shafiei et al. (2015) indicate that Iceland would benefit from an increase in hydropower production under future climates while Spalding-Fecher et al. (2017) imply that the Southern African power pool would adversely be affected under a drying climate. Similarly, impacts on electricity demand vary between regions, indicating a net decrease in demand in colder regions while contrarily, implying a net increase in demand in warmer regions.

Furthermore, several studies indicate limited adverse impacts of gradual changes in climate variables on wind and solar energy production (Tobin et al., 2018; Jerez et al., 2015). Additionally, few studies estimate an increase in wind power generation in some parts of Brazil (Pereira de Lucena et al., 2010) and Croatia (Pašičko et al., 2012). Nevertheless, off-shore wind power plants may need to invest in adaptation measures against sea-level rise (Lise and van der Laan, 2015).

Studies presented so far broadly indicate the adverse impacts of climate change on electricity supply and demand, calling for the power sector to improve its resilience to climate change. Furthermore, although climate change is a global phenomenon, its geography is uneven, showing diverse impacts across the globe. Hence, assessments of these impacts at local levels are needed to facilitate appropriate local adaptation actions.

1.4. Research gaps

While the literature on the subject is extensive, several research gaps remain. Building upon previous studies, this doctoral dissertation aims to address gaps in the literature on the analysis of climate change mitigation and adaptation in the expanding power sector. In particular:

(i). A bottom-up assessment regarding the trade-offs between electrification and the Paris climate target of the Indonesian power sector is still missing.

Previous studies have analyzed the decarbonization of the Indonesian power system (Marpaung et al. (2007); Dasuki et al.; (2001); Purwanto et al. (2015); Stich and Hamacher (2016); Kumar (2016)). Nonetheless, a thorough search of the relevant literature yielded only one related article, i.e., Siagian et al. (2017), which specifically addressed Indonesia's intended nationally determined contribution. However, this study was carried out based on a draft policy document before the COP21 in Paris. Meanwhile, a study that examines the implications of the energy sector's target in the final NDC submitted under the Paris Agreement is still missing.

Moreover, the previous research by Siagian et al. employs the Asia-Pacific Integrated Model/Computable General Equilibrium (AIM/CGE) model for their analysis and mentions the model's limitations in producing technology-rich outcomes, which can be provided by bottom-up-type engineering models. Therefore, a bottom-up analysis using a technology-detailed dataset of the Indonesian power sector in achieving Indonesia's NDC will add to the existing literature on modeling low-carbon energy systems.

(ii). ETL is not represented in the LEAP modeling literature.

Heuberger et al. (2017) listed state-of-the-art energy and electricity system models, incorporating ETL, which includes MESSAGE-MACRO, MARKAL-TIMES, NEMS, POLES, ERIS, GALLM, and ESO-XEL. The LEAP modeling literature, however, has not included ETL thus far.

Since LEAP is claimed to be the de facto standard for developing countries undertaking assessments of low-emission development strategies (Heaps, 2017), it is essential to incorporate ETL into LEAP. Such an effort enables the consideration of cost reductions of low-carbon technologies over time for robust analysis of low-carbon energy transition. ETL often indicates declining costs of relatively new technologies -such as wind or solar- in comparison to more established fossil fuel-based ones. Neglecting this significant change in market forces when developing policy decisions for the rapidly expanding energy sector in developing countries may lead to unnecessary technological lock-ins.

(iii). *Empirical evidence regarding the impacts of weather and climate on the power sector is scarce.*

As discussed in Section 1.3.3 above, previous research has provided projections regarding climate change impacts on the power sector, mostly by employing simulation models. Nevertheless, there have been few empirical investigations about the historical effects of weather and climate on the power sector. Such an investigation on the entire value chain of the power sector will add to the understanding of the risks posed by severe weather events and gradual climate change on electricity supply and demand.

Moreover, existing literature on climate change impacts on the power sector focuses mainly on electricity infrastructure in developed countries, making potential impacts on the power sector in developing countries unexplored (Audinet et al., 2014). Accordingly, the IPCC AR5 acknowledges the scarcity of publications regarding climate change impacts, adaptation, and vulnerability in developing countries (Field C.B. et al., 2014).

Finally, since electric utilities are responsible for ensuring the security and reliability of electricity supply, the impacts of climate variability and change directly affect the utilities' business activities (Audinet et al., 2014). As such, this calls for investigations on direct damage costs suffered by utilities, as well as their responses to disruptive weather and climate, which could be further used to estimate the costs of climate change and the benefits of adaptation.

(iv). *Integrated analysis of climate change mitigation and adaptation of the power sector remains a challenge.*

The IPCC AR5 identifies several challenges in managing trade-offs and synergies between mitigation and adaptation. These include suitable tools for an integrative assessment, stable governance structures, as well as an adequate capacity to design and deploy integrated responses (Pachauri et al. 2014). The report also highlights climate change impacts and the adaptation responses of the energy system as a research gap, urging their integration into the assessment of the climate stabilization path (Clarke et al., 2014).

Section 1.3.1 and 1.3.3 have presented studies that are concerned with climate change mitigation in the power sector and the impacts of climate change on the power sector, respectively. Nevertheless, these studies do not explicitly link climate mitigation efforts of the power sector with the projected impacts of climate change to the sector, let alone asses their multiple effects on the future power sector.

A separate analysis of climate change mitigation, impacts, and adaptations not only jeopardizes the power sector's security and reliability, but it also underestimates the investment needed for expanding the power sector, which is inevitable, especially for the global South. Furthermore, climate change impacts could influence the effectiveness of mitigation options, among other things. Therefore, it is crucial to consider both climate change mitigation as well as adverse impacts and adaptations when analyzing a power system expansion. This requires a clear set of modeling scenarios that consider technological changes when assessing climate change mitigation targets, in addition to the consideration of future climatic regimes when examining climate change adaptation goals.

1.5. Main goal, research questions, and approach

1.5.1. The main goal and research questions

The main **goal** of this doctoral research is to assess the triple nexus of electrification, climate change mitigation, and the climate change adaptation objectives of the power sector. To understand how the power sector may balance these triple objectives, this dissertation addresses the following four core **research questions** (RQ):

RQ1: How could the power sector align electrification and the Paris Agreement goals?

RQ2: How could technological change affect the deployment of low-carbon technologies?

RQ3: How do severe weather and gradual changes in climate variables affect the power system? What are the current adaptation practices?

RQ4: How can one integrate climate change impacts into power system expansion modeling? How might this affect electrification and climate change mitigation goals?

1.5.2. Research approach

I address these research questions by employing a set of methodological steps, as depicted in Fig. 1.2. Modeling is pursued with LEAP and WEAP (Water Evaluation and Planning system) software tools, while extensive data collection is conducted through interviews and focus group discussions (FGDs) with stakeholders from different elements of the power sector supply chain. Thereafter, I gradually advance the current modeling practice by sequentially taking into consideration endogenous technological learning as well as climate change impacts and adaptations (the blue arrows of Fig. 1.2).

<u>The LEAP simulation model:</u>

I use LEAP to assist in answering RQ1, RQ2, and RQ4. LEAP is a tool to evaluate the entire energy system. The essential features of LEAP for addressing the primary goal of this dissertation includes its support for alternative scenario projections, its least-cost optimization modeling of power system expansion, and the calculation of CO_2 emissions.

LEAP consists of three modules: I. Demand, II. Transformation and III. Resources modules (the black boxes of Fig. 1.2). The power system simulation, called the electricity generation module in LEAP, belongs to the transformation module. The electricity generation module simulates electricity supply to satisfy the given demand, based on various input parameters. Accordingly, the resources module calculates the required fuel to generate electricity simulated in the transformation module. The model outputs, which are of most interest given the goal of this dissertation, is the added capacity and electricity generation for each technology, CO_2 emissions, and costs.

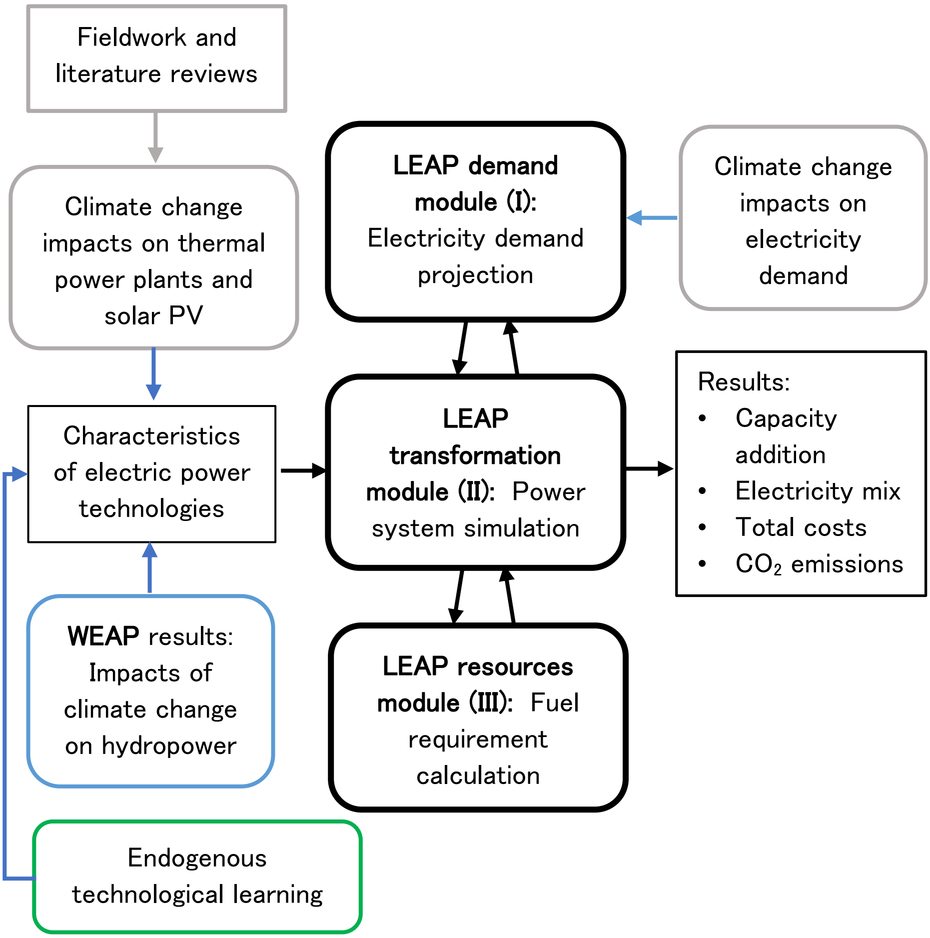


Fig. 1.2: Major analytical components and methodological approach

The simulation of electricity generation consists of three 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. Three, the resource module calculates the primary energy required to generate electricity based on the fuel efficiency of each technology. Additionally, LEAP calculates the power system's total costs based on the costs' input data. Moreover, LEAP includes a technology and environmental database that allows the calculation of CO_2 emissions from the electricity production based on the IPCC Tier 1 emission factor.

In LEAP, the optimal solution is defined as the power system with the lowest total net present value of the total costs over the entire period of calculation (from the base year to the end year). Thus, the optimization setting works through integration with the Open Source Energy Modelling System (OSeMOSYS). LEAP automatically writes the data files required by OSeMOSYS, making use of the same data that were input into LEAP. The results of the optimization are also read back into LEAP so that all relevant results can be viewed in LEAP. In turn, OSeMOSYS depends on a solver software tool for developing decision optimization models. Due to the complexity of the simulations performed in this doctoral research, a more powerful solver, namely the CPLEX optimizer, which is a software toolkit developed by IBM, was used instead of the LEAP built-in GNU Linear Programming Kit.

<u>The WEAP simulation model:</u>

This dissertation employs WEAP for evaluating the impacts of climate change on water availability for hydropower; thus, it supports addressing RQ4. WEAP is a software tool that was also developed by SEI and as such, WEAP and LEAP are sister tools that share many of the same design features and approaches. Furthermore, WEAP has a built-in link with LEAP, allowing the integration of WEAP outputs into the system-wide LEAP model. WEAP can simulate water demand, flows, and storage, as well as pollution generation, treatment, and discharge (Sieber, 2019). The essential features of WEAP employed for the goal of this dissertation are its capability to simulate the water demand and supply of a river basin, taking into account climate variables and competing uses of water.

A WEAP application is initialized by defining the scope of the study, such as the timeframe, spatial boundary, and system components. The present situation regarding water demand and supply is entered into the "Current Accounts" tab. As such, alternative sets of scenarios are developed based on various assumptions; for example, future climates. These scenarios can be evaluated with regard to water sufficiency, cost, and environmental impacts.

WEAP simulation results indicate water availability for hydropower under future climates, and further determines the availability[2] of the hydropower. This data becomes the input for the power system expansion model, allowing for an assessment of the impacts of climate-induced hydropower availability on the power system as a whole.

Fieldwork for data collection:

To address RQ3, I carried out fieldwork from February to March 2018, collecting data regarding climate change impacts on the Indonesian power sector and the sector's adaptation responses. The fieldwork involved in-depth semi-structured interviews and FGDs with representatives of three electric utility companies, covering three head offices, ten power generation plants, the Java-Bali grid operator (load control center), two transmission offices, and two distribution offices. Thus, I interviewed stakeholders that were representative of the various stages of the electricity supply to acquire primary data on the current adverse impacts and adaptation practices in these power sector facilities.

[2]Availability in LEAP is defined as the ratio of the energy produced for a given period to what would have been produced if the process ran at full capacity for a given period (expressed as a percentage)

The power plants being chosen are those major ones in the Java-Bali power system, which account for 35% of the Java-Bali power generation capacity. Meanwhile, the T&D offices where I conducted interviews and FGDs are responsible for 65% and 44% of Java-Bali T&D assets, respectively. The interviews and FGDs are supplemented with secondary data, consisting of utilities' internal reports and published energy sector information that was used to validate and triangulate the results derived from the interviews and FGDs. The secondary data for T&D networks include all T&D assets of the Java-Bali power system. Hence, this dissertation covers the entire Java-Bali T&D networks.

A set of questionnaires, which were structured differently for each target group, were used as guidance for conducting interviews and FGDs. The questionnaires were developed based on the results of a literature review on climate change impacts and adaptations in the energy sector.

1.6. Structure of the dissertation

This doctoral dissertation consists of six chapters. Apart from the General Introduction and the Synthesis chapters, there are four research chapters, each dealing with one specific research question (Fig. 1.3). While Chapter 2 and Chapter 3 give attention to climate change mitigation of the power sector, Chapter 4 focuses on climate change impacts and adaptations. Finally, Chapter 5 brings the two parts together within an integrated analysis framework. The remaining parts of this dissertation proceed as follows:

Chapter 2 analyzes the trade-offs between satisfying the Java-Bali electrification goal with achieving the power sector's emission reduction target under the Paris Agreement. Before discussing the method and analysis results of the electrification and climate change mitigation nexus, the chapter elaborates on various energy models and presents the validation of the Indonesian LEAP model.

Chapter 3 explores various scenarios of the Java–Bali power system expansion to achieve the targets of renewable energy share in 2025 and 2050. This chapter elaborates on how endogenous technological learning could be integrated into the LEAP cost function and shows its effect on the deployment of renewable energy, and subsequently, on CO_2 emissions and costs.

Chapter 4 reports the empirical evidence concerning the effects of weather and climate on the entire elements of the power sector. The chapter also provides estimates of direct losses suffered by electric power utilities as well as adaptation measures taken by the utilities to deal with weather– and climate–related disruptions.

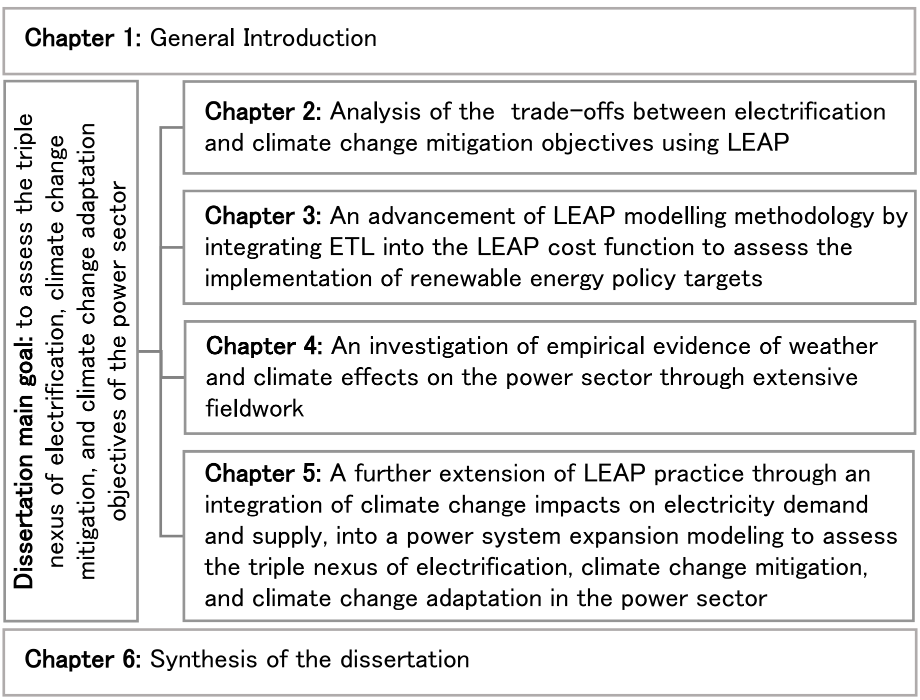


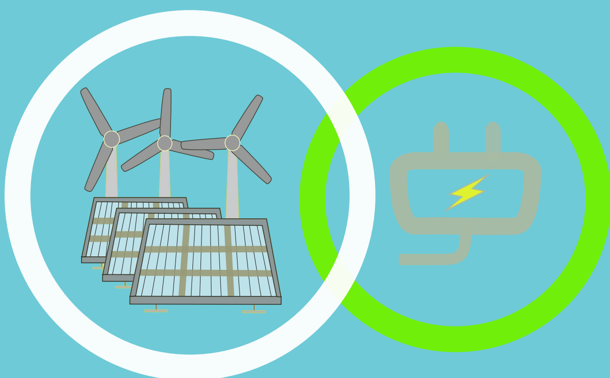
Fig. 1.3: Outlines of the doctoral dissertation

Chapter 5 examines an interplay between electrification, climate change mitigation, and climate change impacts and adaptation in the power sector. Accordingly, adverse climate change impacts on various types of power generation and on electricity demand are incorporated into the simulations of the power system expansion, using LEAP. Hence, the chapter indicates the triple nexus of electrification, climate change mitigation, and climate change adaptation in expanding the Java-Bali power system.

Chapter 6 provides the synthesis of the findings of this dissertation and discusses its innovative contributions as well as its policy implications. The chapter ends with outlining limitations and perspectives for future research.

2

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



Abstract

The power sector in many developing countries face challenges of fast-rising electricity demand in urban areas and the urgency of improved electricity access in rural areas. These development needs are challenged by the vital goal of climate change mitigation. This chapter investigates plausible trade-offs between electrification and CO_2 mitigation in a developing country context, taking Indonesia as an example. By employing LEAP, this chapter incorporates Indonesia's NDC pledge into the modeling of capacity expansion of the Java-Bali power system in Indonesia. Firstly, the LEAP model is validated using historical data of Indonesia's power system. Secondly, four scenarios of the Java-Bali power system expansion from the base year 2015 through to 2030 are developed and analyzed. Results indicate that the shift to natural gas (NGS scenario) decreases future CO_2 emissions by 65 million tons, helping to achieve the CO_2 mitigation target committed to. Likewise, an escalation of renewable energy development (REN scenario) cuts the same amount of the projected CO_2 emissions and, thus, assures meeting the target. The cost optimization simulation (OPT scenario) attains the targeted emission reduction, but at 18% and 12%, lower additional costs compared to NGS and REN, respectively. The cost-effectiveness of CO_2 mitigation scenarios ranges from 36.5 to 44.7 US$/t$CO_2$e.

This chapter is based on a journal article:

Handayani, K., Krozer, Y., & Filatova, T. (2017). Trade-offs between electrification and climate change mitigation: An analysis of the Java-Bali power system in Indonesia. Applied Energy, 208.

2.1. Introduction

Electricity is vital to society today. Global electricity demand in the period of 2002–2012 increased by 3.6% annually, exceeding the annual population growth for the same period (IEA, 2015a). However, nearly 1 billion people worldwide today do not have access to electricity (IEA, 2018b), making the provision of universal access to electricity a vital development objective. Yet, fossil fuel-based electricity production causes GHG emissions measured in CO_2 equivalents (CO_2e). Since 2000, GHG emissions have increased 2.4% a year, reaching 49 GtCO_2e in 2010 (IEA, 2015b), out of which 25% came from electricity and heat production (IPCC, 2014).

The Paris Agreement requires all parties to communicate their Intended Nationally Determined Contributions (INDC), later converted into Nationally Determined Contributions (NDC). Around 99% of the communicated INDCs cover the energy sector (UNFCCC, 2016). 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 research chapter addresses the question of if and how Indonesia may satisfy the growing electricity demand while still meeting climate mitigation targets. 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 cooperation[3]. In the meantime, more than 14 million Indonesians still do not have access to electricity (IEA, 2018b).

This chapter considers both objectives of electrification and climate change mitigation in the simulation of capacity expansion of the most extensive power system in Indonesia, namely the Java-Bali interconnected power system. This chapter analyzes various scenarios of

[3]The Indonesian voluntary pledge is written in its first NDC document submitted to the United Nations Framework Convention on Climate Change (UNFCCC) in 2016.

future power generation in the Java-Bali power system between 2016 to 2030, employing LEAP and a unique dataset from PLN. LEAP is selected over other software tools to suit the modeling needs of this dissertation, through a systematic screening process. Despite the fact that LEAP is actively used -in 85 UNFCCC country reports (Khan et al., 2011) and in more than 70 peer-reviewed journal papers (Connolly et al., 2010)-, publications explicitly discussing the LEAP model validation are limited.

First, I set up the Indonesian LEAP model and run it from the base year 2005 through to 2015. Then, model results are validated against the historical data of the national capacity addition, electricity production, and CO_2 emissions throughout 2006 through to 2015. Secondly, I develop scenarios for future power generation in the Java-Bali power system and analyze the changes in resource utilization and technology deployment that respond to the Paris pledge with 10 power generation alternatives, namely: ultra-supercritical (USC) coal, natural gas combined cycle (NGCC), natural gas open cycle (NGOC), large and small hydroelectric power plant (HEPP), hydro pumped storage (hydro P/S), geothermal, solar photovoltaic (PV), wind power, and biomass.

The chapter adds a number of innovative contributions to the body of the energy modeling literature. Firstly, to the best of the author's knowledge, this chapter is the first to analyze scenarios of power system expansion, which take into account the energy sector's actual CO_2 mitigation targets associated with the Indonesian pledge to the Paris Agreement. This chapter assesses 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, this chapter uses a unique dataset from PLN that represents the 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 factor[4]. Thirdly, this chapter is transparent on the LEAP validation procedure by using ten years of Indonesian electricity supply and demand data. As such, the study 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 chapter is organized as follows: Section 2.2 is the literature review on the decarbonization of the power sector; Section 2.3 presents the methodology and data, including validation of the LEAP model and scenarios development of the Java-Bali power system expansion; Section 2.4 provides the results of LEAP simulations; Section 2.5 discusses the main findings; Section 2.6 concludes the chapter.

2.2. Paris Agreement and decarbonization of the power sector

A number of studies discuss decarbonization of the power sector in developing countries and the implications of their commitments to the Paris Agreement. Grande-Acosta and Islas-Samperio (2017) 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 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 (2017) analyzed the role of low carbon technologies in achieving Kenya's CO_2 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 and Park (2017) investigated the impact of South Korea'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

[4]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 (U.S. NRC, 2017)

South Korean power sector (Lee and Huh, 2017) 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 decarbonize its power sector, which will create unintended consequences, such as the disturbance in stability and integrity due to intermittent renewable energy generation (Guo et al., 2017). Thus, Guo et al. (2017) present an analysis of the decarbonization 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. (2016) assess the impacts of Paris climate targets on water consumption of the power sector in major emitting economies, which include Brazil, China, India, US, EU, and Russia. The study discovered that the fulfillment of long-term climate targets would increase water consumption of power sector, when compared to the business as usual pathways, particularly in the case of China and India.

Studies on the decarbonization of the Indonesian power sector are available in the literature. Marpaung et al. (2005) used a decomposition model to examine two factors (i.e., the technological substitution effect and the demand side effect) that affect CO_2 emissions by considering an influence of external costs on the development of the Indonesian power sector for the period of 2006 to 2025. This study concluded that increasing external cost at a high level allowed for technological substitution, which led to CO_2 emissions reduction by up to 82.5%. Meanwhile, at the low to medium external costs, CO_2 emission reduction was mainly due to the demand-side effect. Shrestha et al. (2009) used an input-output decomposition approach to analyze factors that affect economy-wide change in CO_2, SO_2, and NOx 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 CO_2, SO_2, and NOx emission reductions of 431, 1.6, and 1.3 million tons, respectively, during 2006–2025, as compared to that under the TEP approach. Rachmatullah et al. (2007) used the scenario-planning method to devise a long-term electricity supply plan (1998–2013) of the Java-Bali power system, which included analysis of CO_2 emissions. This study showed that 15% of CO_2 emission could be reduced at an abatement cost of around US$2.8–4.0 per ton. Wijaya and Limmeechokchai (2010) introduced low carbon society actions into the long-term Indonesian power system expansion planning (2007–2025), using the LEAP model. This study concluded that the low carbon society actions reduced external cost by 2 billion US$ as compared to the conventional electricity expansion planning. Purwanto et al. (2015) developed a multi-objective optimization model of long-term electricity generation planning (2011–2050) to assess the economic, environmental, and energy resources adequacy. This study revealed that the power system scenario with high orientation on environmental protection became the most sustainable scenario, yet lacked in terms of Reserve to Production Ratio (R/P) and cost-related indicators. Kumar (2016) investigated the effects of different renewable energy policy scenarios on CO_2 emissions reduction, employing LEAP. The results showed that the utilization of the Indonesian renewable energy potentials reduced up to 81% of CO_2 emissions when compared to the baseline scenario. All of these studies analyzed the long-term power system expansions and their associated CO_2 emissions. However, they did not set specific targets on CO_2 mitigation as a constraint in the simulations of future power generation.

A few studies set a specific target for CO_2 emission in the Indonesian power sector, and simulated patterns of power supply to meet the targets set. Marpaung et al., 2007 developed a general equilibrium model, i.e., Asia-Pacific Integrated Model (AIM)/Enduse for Indonesia, and analyzed the effects of introducing CO_2 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 (2010) analyzed the CO_2 reduction targets scenario for the long-term Indonesian power system expansion planning (2004–2030) using MARKAL. The results showed that constraints on CO_2 emission invoked changes in technology mixes. Similarly, Stich and Hamacher (2016) applied different levels of CO_2 emission reduction targets to the optimized power supply in Indonesia. Their results demonstrated that the CO_2 emission constraints boosted geothermal power expansion to replace the coal-fired power generation. Finally, Siagian et al. (2017) used AIM to simulate energy sector development over the period 2005–2030 under CO_2 constraints stipulated in a draft policy document. Their study indicated carbon prices of US$16 and US$63 (2005)/tCO_2 under 17.5% and 32.7% CO_2 reduction scenarios, respectively.

Neither of these studies is associated with the prevailing Indonesian policy as stipulated in the Nationally Determined Contribution (NDC) as submitted to UNFCCC after the Paris Agreement came into force. Furthermore, an analysis using a bottom-up model that allows considerations of technological complexity in the power sector is still missing. This chapter fills this gap by incorporating the actual energy sector's mitigation targets – i.e., 11% CO_2 reduction on its own effort and 14% CO_2 with international support – into power capacity expansion using a technology-rich energy system model. Hence, the outcomes of this chapter can be used as a reference when formulating the legal framework for curbing CO_2 emissions in the power sector.

2.3. Methodology and data

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

Rigorous models for analyzing long-term planning are necessary to support any optimal allocation of investments. While numerous energy system models are developed and used worldwide (Evans and Hunt, 2009), not all are suitable for performing a technological, economic, and environmental analysis of the national power sector. Consequently, this calls for the careful selection of a model. Urban et al. (2007) 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 (2010) provided an assessment of 12 energy system models suitable for analyzing 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. (2010) reviewed energy system models to identify ones suitable to analyze the integration of 100% renewable energy into various energy systems. The paper presented a brief summary of 37 models, most of them included the power sector in their analysis. However, they varied significantly in their purpose. Based on these three review papers, this chapter filters and identifies energy system models that are open access and suitable for analyzing the technical, economic, 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 2.A (Table 2A.1).

This screening produced a shortlist of 30 models as being potentially suitable for the analysis in this chapter (Appendix 2.A, Table 2A.2). The screening results in the LEAP model being chosen for several reasons. Firstly, it can accommodate the technological complexity of the power system. 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 study, 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 42,000 members in its online platform (Heaps, 2017). 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 analyzing CO_2 mitigation in the power sector worldwide. The LEAP model is employed to explore various scenarios of the energy system development in Taiwan (Yophy et al., 2011), China (Tao et al., 2011), Iran (Amirnekooei et al., 2012), Panama (McPherson and Karney, 2014), Maharashtra, India (Kale and Pohekar, 2014), Pakistan (Perwez et al., 2015), and Africa (Ouedraogo, 2017). LEAP has also been actively applied to study the energy and CO_2 impacts of a power system expansion with a special focus on a particular energy source such as landfill gas in Korea (Shin et al., 2005), nuclear in Korea and Japan (Kim et al., 2011; Takase and Suzuki, 2011) and renewable in Southeast Asia (Kumar, 2016). 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 the power system development. This chapter employs both accounting and optimization methods from LEAP to analyse scenarios of CO_2 mitigation in the Java-Bali power system.

2.3.2. Validation of the Indonesian LEAP model

2.3.2.1. Model setup

I started by setting up a LEAP model of the Indonesian power system from the base year of 2005. After which, I simulated the expansion of PLN's power generation capacity from 2006 to 2015. According to the PLN statistics, coal steam turbine (CST), NGCC, NGOC, diesel generator, hydropower, geothermal, and solar power were the leading technologies employed during this time. 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 2.1 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 from 2005 to 2015. The power system characteristics such as transmission losses and a load shape as well as technological characteristics are also based on the actual values. Meanwhile, the data used for validation of the model results consists of historical electricity generation, past capacity expansion of each technology, and actual fuel consumptions. Appendix 2.B presents detailed information regarding parameters for the Indonesian LEAP model validation.

As mentioned in Section 2.3.1, LEAP has two different settings for simulating electricity generation: accounting settings and optimization settings. Table 2.2 explains the two alternative settings with regard to the capacity addition and electricity dispatch. I compared the simulation results from both of these settings with the actual data of the year 2005–2015 to validate the model performance.

Table 2.1: 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] - Transmission & distribution losses (2005–2015)[a] - Reserve margin* (2005–2015)[b] - Load shape[c] - Power generation capacities[a] - Fuel efficiency[d] - Investment cost of each technology[e] - Operation cost of each technology[a]	- Electricity generation (2005–2015) - Capacity added (2006–2015) - Technology mix of the capacity added - Fuel requirement - CO_2 emissions	- Historical electricity generation (2005–2015)[a] - Historical capacity addition (2006–2015)[a] - Actual technology mix of the capacity added[a] - Fuel consumption[a] - CO_2 emissions[f]

*Reserve margin is the percentage of reserve capacity relative to the capacity needed to meet the normal peak demand. Source: [a]PLN Statistics 2005–2015; [b]Calculated based on peak load and capacity data in PLN Statistics 2005–2015; [c]Drawn based on hourly load data of 2015 (P2B, 2016a); [d]Calculated based on actual electricity production and fuel consumption in 2005 (PLN, 2006); [e]PLN (2005b); [f]Calculated using IPCC Tier 1 emission factor.

Table 2.2: 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.

2.3.2.2. Validation Results

The validation results show that LEAP calculated the total capacity added (Step 1 in LEAP) over the period of 2006 through to 2015 accurately (Table 2.3). LEAP slightly underestimated the added capacity, when compared to the empirical data under both the accounting and optimization settings: by just 0.7% and 1.8%, respectively. As a result, in this 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.

Table 2.3: A comparison of the estimated national capacity added in 2006–2015 with the actual data

Capacity addition	**Empirical data**	**LEAP estimates**			
		Accounting Settings	**Diffe-rence**	**Optimization Settings**	**Diffe-rence**
Cumulative 2006–2015	15.6 GW	15.5 GW	–0.7%	15.4 GW	–1.8%
Technology mix:					
Coal	81%	81%	0%	80%	–1%
Natural gas	19%	19%	0%	20%	+1%

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 the least-cost principle. This is in line with the PLN's capacity expansion policy as stipulated in the Electricity Supply Business Plan (RUPTL) (PLN, 2005).

The results of total electricity production – Step 2 in LEAP – and GHG emissions are shown in Table 2.4. The calibrated LEAP model calculated precisely the total electricity production in the period between 2006–2015, both in the accounting and optimization settings, i.e., 100% and 99.93% accuracy, respectively. Meanwhile, the model overestimated the CO_2

emissions by 2.6% and 2.5% in the accounting and optimization settings, respectively.

Table 2.4: A comparison of the estimated national electricity production and GHG emissions with the actual data

Electricity production and GHG emissions (2006-2015)	**Empirical data**	**LEAP estimate**			
		Accounting Setting	**Diffe-rence**	**Optimization Setting**	**Diffe-rence**
Cumulative electricity production	1,398 terawatt-hour/TWh	1,398 TWh	0%	1,397 TWh	-0.07%
Cummulative GHG emissions	1030 $MtCO_2e$	1057 $MtCO_2e$	+2.62%	1056 $MtCO_2e$	+2.53%

Based on these results, I 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.

2.3.3. Future scenarios development

The validation phase (Section 2.3.2) indicated that the LEAP model estimates of the capacity added, technology mix, cumulative electricity production, and CO_2 emissions were reliable. I moved to scenario analysis of possible future developments of the Java-Bali power system. I developed four scenarios of capacity expansion for the Java-Bali power system. The scenarios were developed based on the changes in LEAP assumptions on the choice of power generation technologies and types of energy sources. All scenarios aimed to reduce CO_2 emissions in line with the Indonesian pledge to the Paris Agreement.

The first scenario (reference) represents the continuity of the present trend that sets the benchmark. The second and third ones -namely: natural gas scenario and renewable energy scenario, respectively- follow The National Energy Policy 2014 (NEP) (Government of The Republic of

Indonesia, 2014). NEP aimed to increase the use of natural gas and new[5] and renewable energy (NRE) to attain a minimum of 22% and 23% shares, respectively, in the national energy mix by 2025. The NRE 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 constraints Indonesia currently faces. Meanwhile, the fourth scenario (optimization scenario) uses the optimization setting of LEAP to find the least-cost solution for the capacity expansion and electricity dispatch. As such, this scenario does not account for the realistic policy constraints per se but instead 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 NDC document, Indonesia is committed to reducing 29% of GHG emissions by 2030 (unconditional target/CM1), compared to the business as usual scenario (Government of The Republic of Indonesia, 2016). A more ambitious target is set at 41% reduction (conditional target/CM2), subject to the availability of financial support from developed countries. Given 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 sector[6] contributed 51% of total emissions over the period of 2000-2012, while the energy sector contributed 32% over the same period (Government of The Republic of Indonesia, 2015b). With no mitigation policy, the energy sector alone is expected to produce up to 1,669 million tCO_2e emissions in 2030 (Government of The Republic of

[5] The term "new energy" is defined as energy that is stemmed from new technologies such as nuclear and hydrogen (Government of The Republic of Indonesia, 2014)
[6] Including land use change

Indonesia, 2015b). These emissions consist of emissions from power, transportation, and other energy sub-sectors. The emission reduction targets for the energy sector are 314 million tons (CM1) and 398 million tons (CM2) or equivalent to 19% and 24% of the energy sector's baseline emission in 2030, respectively, under CM1 and CM2. Yet, the NDC document does not specify the CO_2 emission baseline for the power sector alone. Hence, for all practical purposes, I assume that the power sector contributes proportionally to the national energy sector target. Accordingly, I 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, 19% and 24% by 2030 are the targets for setting up the scenarios.

To quantify possible pathways of reaching these competing targets, I specify four scenarios of the Java-Bali power system expansion for the period 2016-2030 as follows:

(i). *Reference scenario (REF):* In the year 2015, coal-fired power plants (CFPPs) were the dominant technology in the Java-Bali power system. The net capacity of the coal power plants was 17.3 MW or 55% of the total capacity in the Java-Bali power system (P2B, 2016a). The natural gas power plant constituted 34% of the total capacity, while the renewable capacity share was only 11%, which consisted of geothermal (8%) and hydro (3%). Biomass, wind power, and solar PV 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 modeling horizon. This pathway does not incorporate any CO_2 mitigation policies and continues the historical capacity expansion policy based merely on cost-optimization (PLN, 2016b). 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.

(ii). *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. I ran this scenario in two versions. The NGS1 scenario aimed to achieve the 19% CO_2 reduction target compared to the REF scenario, relying entirely on own efforts without any support from international partners. The NGS2 scenario assumes international partners provide support to Indonesia, and this curbs the CO_2 emissions by 24% compared to the REF scenario.

(iii). *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 the 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 19% CO_2 reduction target and REN2 scenario for the 24% CO_2 reduction target.

(iv). *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 CO_2 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 19% and 24% CO_2 reduction targets, correspondingly.

2.3.4. Input data

The data source and methodology to calculate the parameters of the Java-Bali power system are provided in Table 2.5. Rather than relying on the generic LEAP default values, I use national and regional data. Thus, most of the input parameters were collected from governmental reports and PLN. Since PLN is the sole owner and operator of Indonesia's T&D networks, it also records and manages electricity dispatch from IPPs.

Table 2.5: Summary of model input parameter

Input Data	Value	Source
Annual demand growth 2016-2030	6.8% - 7.5%	Refers to the RUPTL estimates (PLN, 2017b)
T&D losses	7.9% - 8.5%	Refers to the draft RUKN estimates (KESDM, 2015)
System load shape	Appendix 2.C	Based on hourly demand data in 2014 (P2B, 2016b)
Reserve margin	35%	Refers to the RUKN criteria (KESDM, 2015)
Capacities of existing power plants	Appendix 2.C	(P2B, 2016a)
Merit order* in the accounting setting:		Maintained according to the P2B dispatch order (P2B, 2016a)
- 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 LEAP technology database (Heaps, 2017)
Discount rate	12%	The discount rate used by PLN (JICA, 2010)

*In the accounting setting of LEAP, merit order is the order in which a power plant will be dispatched. **P2B = the Java-Bali load control center

The demand projection for the year 2016 to 2025 is calculated based on the estimated demand growth in RUPTL (PLN, 2017b). Meanwhile, the demand projection for the remaining years (2026 to 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 (KESDM, 2015). The energy load shape is drawn in the LEAP model based on the historical hourly load data collected from P2B, as shown in Appendix 2.C, Figure 2C.1 (P2B, 2016b). The planning reserve margin was set at 35% following the criteria in the draft National Electricity General Plan (RUKN) 2015–2034 (KESDM, 2015).

The calculation of electricity generation in LEAP depends on the input of the projected electricity demand in the demand module (Chapter 1, Fig. 1.2). Thereafter, the electricity generation module in LEAP assigns technologies to satisfy the electricity demand. One limitation in LEAP is that the model does not provide for the expansion of T&D networks. Hence, I assume that there are no constraints in the T&D networks, meaning that the electricity supply can be transmitted at any time to any T&D substation.

The type of existing power generation technologies in the Java–Bali power system includes CST, NGCC, NGOC, diesel generator, HEPP, and geothermal. For capacity expansion, I consider adding unexploited renewable potentials, namely, biomass, wind turbine, and solar PV.

The existing coal power plants in Java–Bali use conventional technologies, which have relatively lower efficiencies compared to the supercritical (SC) and USC technologies. According to RUPTL, to improve efficiency and reduce CO_2 emissions, the future coal power plant's development in the Java–Bali power system would only consider SC and USC technologies (PLN, 2016b). Thus, this dissertation only considers USC coal technology for the new coal capacity addition. To date, there are no nuclear power plants in Indonesia. In the future, the development of large-scale nuclear energy supply is possible, as indicated in NEP. However, it is considered as the last option after maximizing the use of renewable energy sources. Therefore, this chapter assumes no nuclear deployment during the time horizon of the simulations (2016–2030).

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 reliable base year data, which was used as a reference for developing power expansion scenarios. The capacities of existing power plants in the Java-Bali power system are presented in Appendix 2.C, Table 2C.1.

Meanwhile, technology data for future capacity expansion were retrieved from various studies, as shown in Table 2.6. The cost characteristic of power generation technologies refers to the cost assumptions of the world energy outlook (WEO) model (OECD/IEA, 2017). Costs data that was not presented in the WEO model 2016 were taken from the Indonesian Energy Outlook (IEO) 2016, 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 (PLN, 2016c), while biomass fuel cost was sourced from ASEAN Energy Centre (ACE) study (ACE, 2016). 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 concerning renewable energy, as it can only be utilized locally. Hence, the simulation of renewable energy expansion takes into account the potential of renewable energy in the Java-Bali islands. For practical reasons, I assume that the publicly available data for the Indonesian renewable energy potential (Chapter 1, Table 1.2) can be exploited over the time horizon of this study. Furthermore, I assume that Indonesian natural gas reserves could be utilized for power generation without any constraint.

Table 2.6: Characteristics of technologies in the Java-Bali LEAP model

Technology	**Lifetime (years)[a]**	**Efficiency (%)[b]**	**Maximum Availability (%)*[c]**	**Capacity credit (%)**[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$/ton
NGCC	25	57	80	100	817	24	3.8	7.6 US$/MMBTU
NGOC	25	38	80	100	439	21	3.8	7.6 US$/MMBTU
Hydro	35	100	41	51	2200	56	3.8	–
Mini hydro	35	100	46	58	3350	67	3.8	–
Hydro P/S	35	95[c]	20	25	1050[c]	54[c]	3.8	–
Geothermal	20	10	80	100	2675	53	0.7	–
Solar PV	20	100	17	22	1953	20	0.4	–
Wind power	20	100	28	35	1756	44	0.8	–
Biomass	20[h]	35	80	100	2228	78	6.5	11.67 US$/ton[i]

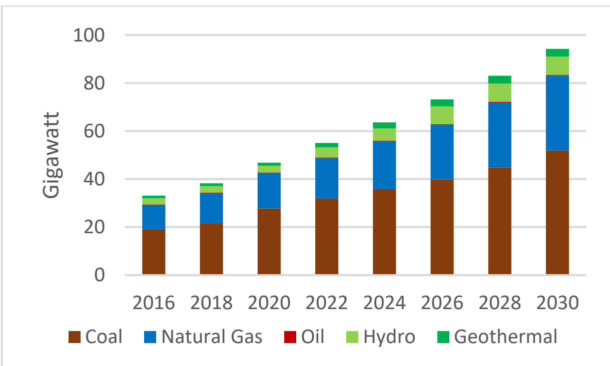
Note: kW= kilowatt; MWh = megawatt-hours; OM = operation and maintenance; MMBTU = million British thermal units.
*Maximum availability in LEAP is defined as the ratio of the maximum energy produced to what would have been produced if the process ran at full capacity for a given period (expressed as a percentage) (Heaps, 2017).
**Capacity credit in LEAP is defined as the fraction of the rated capacity considered firm for calculating the reserve margin, which is calculated based on the ratio of availability of the intermittent plant to the availability of a standard thermal plant (Heaps, 2017).
[a]IEA and OECD/IEA (2015); [b]OECD/IEA (2017)[w]; [c]DEN (2016); [d]calculated based on the ratio of availability of the intermittent plant to the availability of a standard thermal plant (Heaps, 2017); [e]PLN (2016c); [f]Rothwell and Rust (1997); [g]IEA and NEA (2015); [h]IRENA (2012); [i]ACE (2016).

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

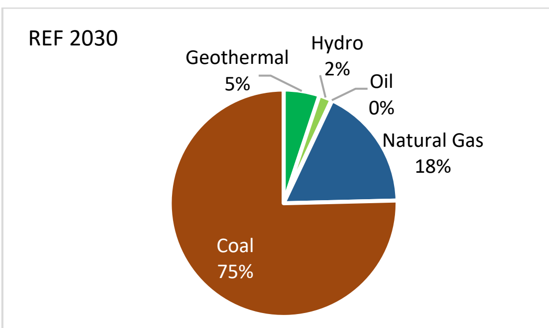
2.4.1. Reference scenario (REF)

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 GW (Fig. 2.1.a). The capacity mix in 2030 is equivalent to 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%) 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. 2.1.b).



(a)



(b)

Fig. 2.1: Reference scenario: Power generation capacity 2015-2030 (a); Electricity generation mix in 2030 (b)

The resulting CO_2 emissions in 2030 are 339 million tCO_2e or nearly threefold of the emissions in the base year. These are the baseline for the CO_2 reduction in the mitigation scenarios (NGS, REN, and OPT). Table 2.7 shows the CO_2 emissions baseline and reduction targets.

Table 2.7: Emission reduction targets against REF scenario

CO_2 emissions level in 2030 (REF), million tCO_2e	CO_2 reduction target in 2030 (%)	CO_2 emission reduction in 2030, million tCO_2e
339	19%	64.4
339	24%	81.4

2.4.2. Natural gas scenario (NGS)

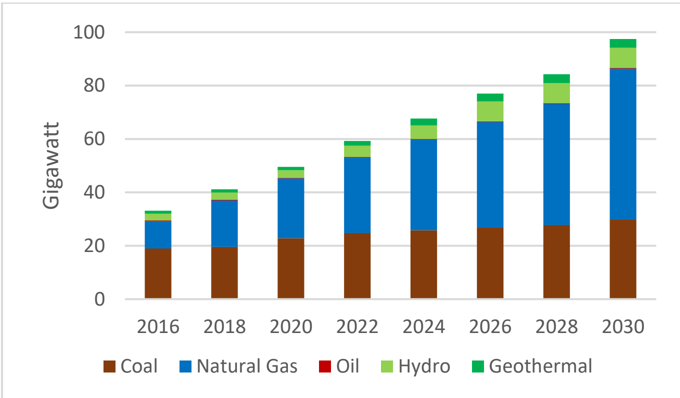
The results of the LEAP simulations for the NGS scenario indicate that switching from coal to natural gas alone can already deliver both 19% and 24% CO_2 reduction targets. This switching requires around 0.36 billion toe of natural gas, which is equivalent to 9% of the Indonesian natural gas reserve.

NGS1 scenario aiming at the 19% CO_2 reduction:

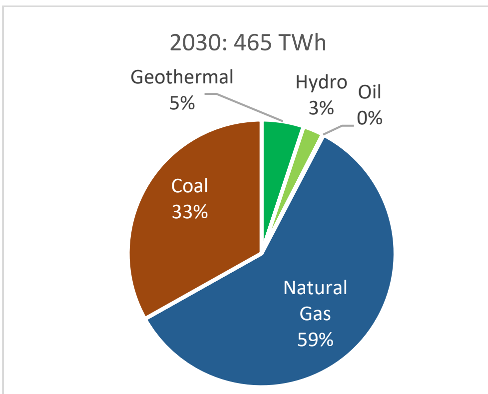
In NGS1, the natural gas capacity in 2030 expands up to 56.5 GW, a fivefold increase in the capacity over 2015. It is a 25% increase in the gas share in the capacity mix as compared to REF (Fig. 2.2.a). Consequently, the coal capacity share decreases from 52% in REF down to 31% in NGS1. Compared to REF, the corresponding electricity production from natural gas increases significantly. In NGS1, natural gas constitutes 50% of the electricity generation in 2030, nearly threefold compared to its share in REF. Accordingly, coal power generation decreases from 75% in REF to 42% in NGS1.

NGS2 scenario aiming at the 24% CO_2 reduction:

In order to reduce the CO_2 emissions by 24% against REF, further expansion of natural gas capacity is required. The simulation results indicate that it takes an additional 6.2 GW of natural gas capacity when compared to NGS1. Consequently, the share of natural gas power generation in 2030 rises to 59%, which is 9% higher than NGS1 (Fig. 2.2.b). Meanwhile, the coal capacity share declines to 24%, leading to a reduced percentage of the coal power generation to 33% as compared to 75% in REF.



(a)

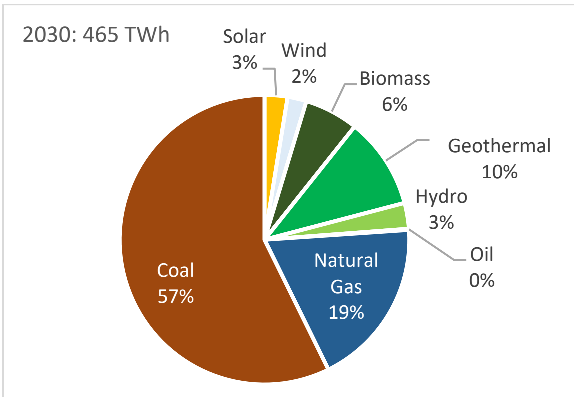


(b)

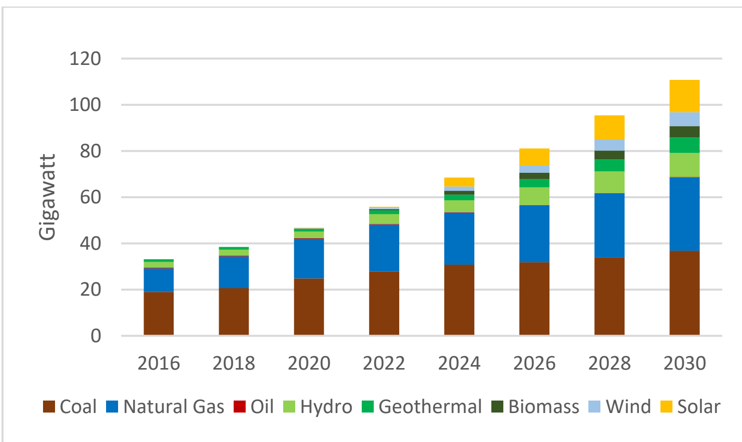
Fig. 2.2: Natural gas scenario: Power generation capacity (NGS1, 19% target) (a); Electricity generation mix in 2030 (NGS2, 24% target) (b)

2.4.3. Renewable energy scenario (REN)

In REN, the capacity of renewable energy increases significantly in order to attain both 19% and 24% CO_2 reduction targets. Accordingly, the corresponding electricity production from renewable energy also grows in both REN1 and REN2 scenarios (Fig. 2.3). 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 (PLN, 2017b). By 2030, the solar PV capacity adds up to 8 GW and 14 GW, respectively, in REN1 and REN2. Furthermore, the capacity of wind power reaches 4 GW and 6 GW by 2030 in REN1 and REN2, respectively. Meanwhile, no specific target is set for biomass, although the RUPTL mentions the plan to add 0.1 GW of municipal waste power plants. I assume that 4 GW and 5 GW of biomass capacities are added in REN1 and REN2, respectively, out of the total 7.4 GW biomass potentials of the Java-Bali islands.



(a)



(b)

Fig. 2.3: Renewable energy scenario: Electricity generation mix in 2030 (REN1, 19% target) (a); Power generation capacity (REN2, 24% target) (b)

REN1 scenario aiming at the 19% CO_2 reduction:

The renewable capacity in REN1 adds up to 33 GW or threefold of the renewable capacity addition present in REF. Renewables now account for 31% of the total power generation capacity in 2030, split between hydro (9.8%), geothermal (6.3%), wind power (3.8%), biomass (3.8%), and solar PV (7.6%). Consequently, the share of renewable electricity generation increases by up to 24% of the total power generation in 2030, which is three times higher than that in REF.

REN2 scenario aiming at the 24% CO_2 reduction:

To accomplish the 24% CO_2 reduction target, 9 GW of renewables are added on top of their capacity in REN1. In 2030 the renewables capacity reaches 42 GW constituting 38% of the total power generation capacity. The capacity is shared between hydro 10.3 GW, geothermal 6.7 GW, wind 6 GW, biomass 5 GW, and solar PV 14 GW. Meanwhile, the share of renewable electricity generation adds up to 28% as compared to 7% in REF.

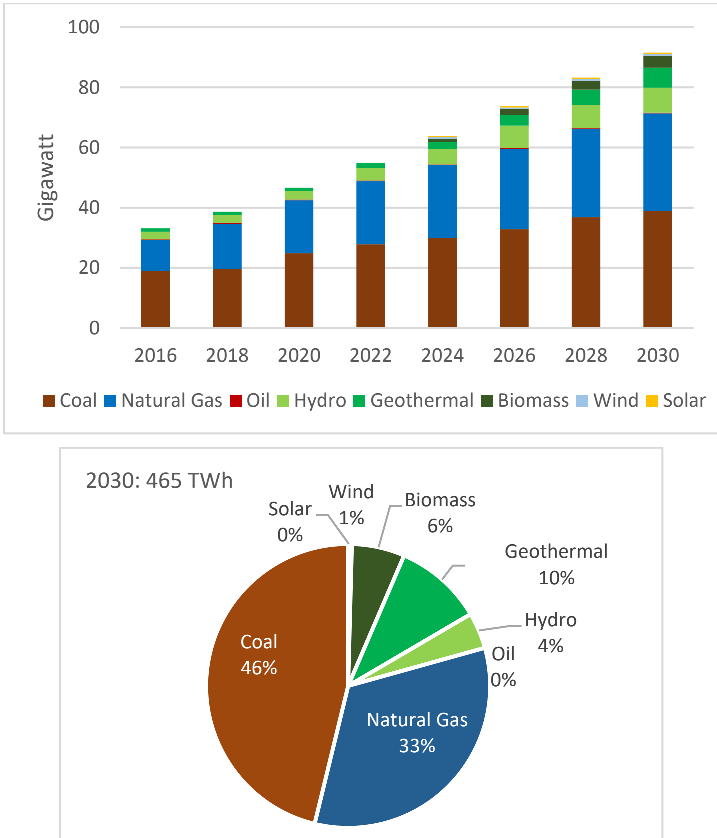
2.4.4. Optimization scenario (OPT)

Based on the simulation results of the OPT scenario, the least-cost option for meeting the Paris target is to expand both renewable energy and natural gas capacities, resulting in a significant decrease in coal capacity compared to REF (Fig. 2.4).

OPT1 scenario aiming at the 19% CO_2 reduction:

In OPT1, by 2030, the renewables capacity accounts for 20 GW (Fig. 2.4.a). This is a significant increase from 10.8 GW in REF, and consists of hydro (8.4 GW), geothermal (6.6 GW), biomass (4 GW), wind (0.5 GW), and solar PV (0.5 GW). The natural gas capacity increased by 4% from 31.3 GW in REF to 32.5 GW in OPT1. Meanwhile, the coal capacity decreases significantly (25%) from 51.8 GW in REF down to 38.8 GW in OPT1.

Thus, the OPT1 cost-efficient electricity generation mix in 2030 consists of coal (56%), natural gas (23%), and renewables (21%). Despite its decreased capacity compared to REF, the production share of coal remains the highest due to its dominance in the base year (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.



(a)

(b)

Fig. 2.4: Optimization scenario: Power generation capacity (OPT1, 19% target) (a); Electricity generation mix 2030 (OPT2, 24% target) (b)

OPT2 scenario aiming at the 24% CO_2 reduction:

The results of the OPT2 scenario show that the 5% supplementary CO_2 reduction can be attained through partial substitution of coal by natural gas. These produce an electricity generation mix comprising of coal (46%), renewables (21%), and natural gas (33%), in the year 2030 (Fig. 2.4.b).

2.4.5. CO_2 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 2.8 shows the total costs for all scenarios. The costs of CO_2 mitigation are the difference between the total costs of the Java–Bali power system expansion in REF and in each mitigation scenario. The total cost of the Java–Bali power system expansion in REF is equal to 0.1% of the cumulative national GDP during the study period[7]. The model estimates the increased costs of 4.7%, 5.3%, and 6% in OPT1, REN1, and NGS1, respectively, to reduce 19% of the CO_2 emissions compared to REF. Furthermore, reducing 24% of emissions leads to the increased costs of 6.1%, 7.1%, and 7.3% in OPT2, NGS2, and REN2, respectively, which can be covered by climate finance as mandated by the Paris Agreement. The CO_2 mitigation costs in each scenario range from 0.005% to 0.008% of the total GDP.

Table 2.8: Total costs of power system expansion in different scenarios

Scenarios	**CO_2 reduction against REF in 2030 (million tCO_2e)**	**Total costs (billion USD)**	**CO_2 mitigation costs (billion USD)**	**Cost–effectiveness of CO_2 mitigation (USD/tCO_2e)**
Reference (REF)	0	49.9		
Natural gas 1 (NGS1)	64.6	52.9	3.01	46.6
Natural gas 2 (NGS2)	82.0	53.4	3.52	42.9
Renewable energy 1 (REN1)	64.6	52.6	2.66	41.2
Renewable energy 2 (REN2)	81.5	53.5	3.63	44.7
Optimization 1 (OPT1)	64.7	52.3	2.35	36.3
Optimization 2 (OPT2)	81.5	53.0	3.05	37.5

[7]Assuming annual GDP growth of 4.5%

The NGS 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 CO_2 mitigation scenario is OPT, followed by REN. The optimization method in OPT ensures the lowest total costs of the power system expansion in meeting the mitigation target. The OPT scenario covers all technologies employed in REF with the addition of biomass, wind, and solar PV technologies. However, the optimal mix can be sensitive to the input assumptions, such as the relative performance of different technologies or future costs. I keep it aside as a subject for Chapter 3.

Table 2.8 also shows the cost-effectiveness of the CO_2 mitigation scenarios. For the 19% CO_2 reduction target, the abatement costs are 36.3, 41.2, and 46.6 US$/t$CO_2$e in OPT1, REN1, and NGS1, respectively. Meanwhile, for the 24% CO_2 reduction target, the abatement costs are 37.5, 42.9, and 44.7 US$/t$CO_2$e in OPT2, NGS2, and REN2, respectively.

2.5. Discussions

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-fueled power plants remain dominant until the end of the study period. As a result, the CO_2 emissions in 2030 are nearly triple those witnessed in 2015.

2). In the context of the Java-Bali power system, the power sector target associated with the Paris pledge – 19% or 24% reduction – is achievable under the proposed capacity expansion scenarios. The NGS scenario results in a substantial addition of natural gas capacity, i.e., 47 GW and 54 GW under the NGS1 and NGS2 scenarios, respectively. This indicates that the single substitution of coal by natural gas can reduce emissions by 19% and 24% from REF. REN scenarios lead to the addition of the renewable capacity of 29 GW and 38 GW under the

REN1 and REN2 scenarios, respectively. The OPT scenarios that focus on the cost-minimization result in expansions of both renewable energy and natural gas capacities.

3). Total costs of the Java-Bali power system expansion under the REF scenario are equal to 0.1% of the Indonesian GDP during the analysis period. Any of the CO_2 mitigation efforts aligned with the Java-Bali capacity expansion increases the costs from 5% to 7% of the REF cost. The cost-effectiveness of CO_2 mitigation scenarios ranges between 36.3 and 46.6 US$/t CO_2e.

Overall, these findings indicate 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 goal 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, results of this chapter are aligned with other studies regarding the implication of the Paris Agreement on the power sector in developing countries, for example, the case of Botswana (Baek et al., 2019) and Kenya (Dalla Longa and van der Zwaan, 2017).

Providing reliable and affordable electrical energy for the entire population is a vital development goal of the Indonesian Government. Therefore, 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 (Gumelar, 2017; Direktorat Jenderal Anggaran, 2017). Thus, it is paramount to maintain low electricity production costs. As such, the Indonesian power sector development follows the 'least costs' principle, with electricity supply options are chosen based on the lowest cost (PLN, 2016b). 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 the consumer and the size of the government subsidy.

2.6. Conclusions

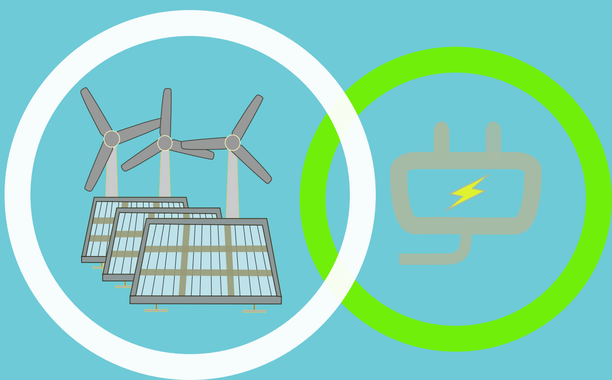
Assuring electricity access for the entire population is still a vital national development goal for many developing countries, including Indonesia. Likewise, climate change mitigation and adaptation are also central policies due to the country's vulnerability to climate change impacts. This chapter analyzed plausible trade-offs between electrification and climate change mitigation goals in the Java-Bali islands. The focus was on alternatives that could allow Indonesia to satisfy the future electricity demand, while also meeting its Paris climate targets. LEAP was chosen for performing the analysis after a systematic review of different models (Appendix 2.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 analyzed.

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 CO_2 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 the government's subsidy.

This chapter has incorporated Indonesia's NDC targets into 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 (Rubin et al., 2015) – and analyzes their impact on the robustness of the power system expansion scenarios within the CO_2 mitigation constraints.

3

From fossil fuels to renewables: An analysis of long-term scenarios considering technological learning



Abstract

This chapter analyzes a diffusion of renewable energy in a power system considering technological learning. The chapter explores long-term scenarios for capacity expansion of the Java-Bali power system in Indonesia, considering the country's renewable energy targets, by applying the LEAP model with an integration of technological learning. Results reveal that, at the medium and high pace of technological learning, the total costs of electricity production to achieve the long-term renewable energy target are 4% to 10% lower than the scenario without considering technological learning. With respect to technology, solar PV and wind become competitive with other types of renewables and nuclear. Moreover, the fulfillment of the renewable energy targets decreases CO_2 emissions by 25% compared to the reference scenario. Implications of these findings indicate that energy policies should focus on the early deployment of renewables, upgrading the grid capacity to accommodate variable renewable energy, and enabling faster local learning.

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3.1. Introduction

Renewable energy is a critical component for combating climate change. In fact, most of NDCs submitted by countries under the Paris Agreement include renewable energy as their measure to address climate change (IRENA, 2017). The implementation of NDCs will add at least 1.3 terawatts to the global renewable installed capacity. This ambitious target would need a considerable investment cost—1,700 billion USD by 2030, according to the International Renewable Energy Agency (IRENA) estimate.

The high upfront expense for the installation of renewable technologies is one of the factors that hinder the deployment of renewable energy. However, the capital costs of energy technologies are known to decline over time due to cost-reducing technological changes, usually referred to as learning (IEA, 2000; Lafond et al., 2017; McDonald and Schrattenholzer, 2001; Rubin et al., 2015; Watanabe, 1995). The concept of the learning effect has been widely used and analyzed empirically in many applications (Grübler et al., 1999). The earliest example is Wright (1936), who reported that unit labor costs in airframe manufacturing declined with accumulative experience measured by cumulative output.

Cost savings brought up by technological learning are especially attractive for developing countries, which are still facing rapid growths of electricity demand while also pledging their NDCs. This case applies to Indonesia, the fourth most populous country in the world. Electricity demand in the country is projected to grow at an average of 8.3% per year in the next decade (PLN, 2017b). Meanwhile, it pledges to reduce 29% of its greenhouse gas emissions against its business-as-usual scenario by 2030 (Government of The Republic of Indonesia, 2016). While, in 2015, renewable energy only accounted for 4% of the national energy mix[8] (DEN, 2016c), the most recent national energy policy (NEP) requires it to increase by 23% in 2025 and 31% in 2050 (Government of The Republic of Indonesia, 2014). In the context of the power sector, renewable energy currently accounts for 10% of the national electricity generation mix[9] (PLN, 2016a). RUPTL 2016-2025 estimates an increase in unit costs of electricity production by 22% to realize the NEP target in the power sector by 2025. Such a raise, if it occurs, will cause a burden on the power sector and, in turn, the national economy. Yet, these projections neglect the learning process of electric power technologies. As discussed above, technological learning may reduce the unit costs of electricity production, making investments in renewable energy technologies more economically attractive.

Given the essential role of technological learning, it is necessary to consider it when projecting a long-term electricity supply. Accordingly, this chapter integrates technological learning into the LEAP model to explore a number of electricity expansion scenarios. LEAP has been actively used for assessing renewable energy expansion in many countries, such as Pakistan (Ishaque, 2017), Bulgaria (Nikolaev and Konidari, 2017), Ghana (Awopone et al., 2017), Thailand (Wongsapai et al., 2016), Iran (Eshraghi and Maleki, 2016), Indonesia (Kumar, 2016), India (Kumar and Madlener, 2016), Malaysia (Samsudin, 2016), Brazil (De Andrade Guerra et al., 2015), Korea (Park et al., 2013), and Lebanon (Dagher and Ruble, 2011). Despite its extensive use, little attention has been paid to incorporating technological learning in the LEAP model, which likely results in underestimating the future deployment of renewable energy.

Focusing on the Java-Bali power system, this chapter develops scenarios for the system's capacity expansion from 2016 through to 2050.

[8]Energy mix is a set of various primary energy sources used to meet energy needs in a region (ton oil equivalent and % contributions)

[9]Electricity generation mix is a set of primary energy sources that constitute the total electrical energy production in a region (Megawatt hour and % contributions).

Moreover, this chapter applies a learning model for each power generation technology into the LEAP cost function. The simulation results are analyzed in terms of energy, costs, and CO_2 emissions.

The innovative contribution of this chapter is twofold. First, methodologically, it moves beyond the current practice of LEAP usage by incorporating a learning model with respect to energy technologies into the LEAP cost function. Although there are some energy system models that have included technology cost learning, such as MESSAGE-MACRO, MARKAL-TIMES, NEMS, POLES, ERIS, GALLM, and EXO-XEL (Heuberger et al., 2017), to the best of our knowledge, this dissertation is the first to include technological learning endogenously in LEAP. Secondly, this chapter adds an understanding regarding the role of technological learning in driving the transition from fossil-fuel-based power generation to a lower-carbon power system in the context of developing countries.

The remainder of this chapter is organized as follows: Section 3.2 presents the literature review; Section 3.3 explains the methodology, scenarios, and the model input parameters for the future Java-Bali power system; Section 3.4 discusses the results of model simulations; Section 3.5 presents the main findings of this chapter; Section 3.6 concludes the discussions.

3.2. Technological learning

The development of technology is not an autonomous, independent process. Instead, it evolves from many interactions within social systems as well as from experience in using the technology itself (Barreto, 2001). The process of technological change requires considerable time from innovation to widespread diffusions, such as what has occurred in the past concerning the global technology transitions from traditional biomass to coal-based technology and from coal-based technology to electricity and petroleum-based technologies (Wilson and Grubler, 2011).

The development and introduction of new technologies involve a learning process that results in the improvement of the production process and product, which, in turn, often makes the costs lower (GEA, 2012). The learning process starts from the first practical use of a new technology until its maturation stage (Sagar and van der Zwaan, 2006). Learning is a crucial element of the early adoption of technologies, and it indicates the experiences gained through the practical use of technology and contributes to cost reduction over time (Sagar and van der Zwaan, 2006). Since learning is a self-enforcing process, more accumulated experiences in technology lead to lower cost, and more increase in technology competitiveness leads to even more accumulated experience (Gillingham et al., 2008). As such, it is not always the case that new technology is used because it becomes cheap, but also technology becomes cheap because of its increased use and learning process (Berglund and Söderholm, 2006). In addition to cost reduction, learning can also lead to greater proficiency in technology operation as well as institutional transformation necessary to allow the widespread use of new technologies (Sagar and van der Zwaan, 2006).

The concept of the learning effect has been widely used since its first appearance in the economic literature, and it was empirically verified (Berglund and Söderholm, 2006). The learning process triggering cost reduction is expressed as a function of the accumulation of knowledge and experience related to R&D expenditures, the production, and the use of technology (Kahouli-Brahmi, 2008). Quantification of these learning patterns is presented in the literature using the so-called one-factor and multi-factor learning curves (Kahouli-Brahmi, 2008; Rubin et al., 2015). The former is the most widely used method for endogenously forecasting changes in technology costs. Its experience performance is indicated by the cumulative installed capacity or cumulative production.

The term “learning rate” is used to express the experience gained from using technology and the corresponding technological progress in its production. It denotes the percentage by which a unit cost declines with every doubling of the cumulative production. In other words, it is a fraction by which the unit price of energy service (such as electricity) declines with every doubling of its installed capacity (Sagar and van der Zwaan, 2006). The corresponding change in price compared to its previous price with each doubling of capacity is referred to as the "progress ratio" (Berglund and Söderholm, 2006). A progress ratio of 75% indicates that the costs of technology have declined to 75% of its previous level after a doubling of its cumulative capacity. In this case, the corresponding learning rate is 25%.

The multi-factor approach includes factors beyond the cumulative installed capacity or production that contribute to technology cost reduction, such as R&D spending, knowledge spill-overs, and economies of scale (Rubin et al., 2015). However, due to data requirements and theoretical limitations, this approach is less prevalent in the literature compared to the one-factor model (Farmer and Lafond, 2016; Rubin et al., 2015).

3.3. Methodology and data

3.3.1. The LEAP model

A summary of LEAP methodology has been discussed in Section 1.6. The following sections elaborate on the LEAP framework for calculating electricity demand, capacity expansion, total costs, and GHG emissions

3.3.1.1. Electricity demand projection

In this chapter, the demand for electricity is calculated based on the demand growth projection stipulated in RUPTL 2016-2025 and IEO 2014. Hence, the electricity demand in a specific year is the sum of electricity demanded in the previous year and its anticipated growth:

$$ED_t = (ED_{t-1} * EDG_{t)}) + ED_{t-1}, \qquad \text{Eq. 3.1}$$

where ED_t is the electricity demand in year t, and EDG_t is the percentage of growth in the electricity demand in year t.

Total electricity demand in the power system for a specific year (TED_t) is calculated as the sum of electricity demanded and electricity losses (EL_t) during the electricity transfer through the T&D networks in that year:

$TED_t = ED_t + EL_t$ and Eq. 3.2

$EL_t = ED_t * TL_t$, Eq. 3.3

where TL_t is the percentage of T&D losses in year t.

3.3.1.2. Capacity expansion in LEAP

The capacity of a set of technologies can be added both exogenously and endogenously in LEAP. I specify exogenously the previously existing capacities as well as committed additional capacities, such as the power plants that are currently under construction. Furthermore, the capacity of hydro-pumped storage is also added exogenously following the RUPTL assumptions (PLN, 2016b)

For the endogenous capacity addition, LEAP calculates the amount of capacity to be added using the Eqs. 3.4, 3.5, and 3.6 below (Awopone et al., 2017; Heaps, 2017). In the reference scenario, which uses the accounting setting, I specify the types of the power plant to add, but LEAP decides when they will be added based on the system's requirement. In the renewable energy scenarios, which make use of LEAP's optimization capability, LEAP decides what types of technology should be added and when it will be added based on the least-cost principle and the set constraints. In these scenarios, I set the minimum capacity of natural gas power plants to be added each year as intermediate and peak plants, as well as for balancing the variability of intermittent renewable energies.

$C_{En} = D_p(PRM - RM)$, Eq. 3.4

$D_p = \frac{ED}{LF * 8760}$, and Eq. 3.5

$RM = \frac{C_p - D_p}{D_p}$, Eq. 3.6

where C_{En} is the endogenous capacity addition, D_p is the peak electricity demand, PRM is planning reserve margin, RM is the reserve margin before addition, ED is electricity demand, LF is the load factor (calculated as the ratio of the average load and the peak load), and C_p is the capacity before addition.

3.3.1.3. Total costs calculation

The total cost of the power system is the total net present value of the system costs over the entire period of calculation:

$$TC = \sum_t^{N_t} \sum_p \frac{1}{(1+d)^t} (K_c * Ca_t + foc_t * Ca_t + Voc_t * P_t + Fc_t), \quad \text{Eq. 3.7}$$

where TC is the total cost, N_t denotes the entire years from 2016 through to 2050, p is the process (technology), d is the discount rate, K_c is the initial capital cost, Ca_t is the capacity in year t, foc_t is the fixed operation and maintenance costs in year t, Voc_t is the variable operation and maintenance costs in year t, P_t is the output power in year t, and Fc_t is the fuel cost in year t.

3.3.1.4. CO_2 emissions calculation

CO_2 emissions from electricity production are calculated as follows (Feng and Zhang, 2012):

$$CE = \sum_p \sum_f EF_{f,p} * \frac{1}{E_p} * P_p, \quad \text{Eq. 3.8}$$

where CE is the CO_2 emissions, $EF_{f,p}$ is the CO_2 emission factor from one unit of primary fuel type f consumed for producing electricity through technology p, E_p is the efficiency of technology p, and P_p is the output power from technology p.

3.3.2. Integration of the learning model

LEAP does not provide a built-in expression for capturing technological learning. Thus, I integrate the one-factor learning model into LEAP by adding expression in LEAP, representing the learning curve of electric power technologies. I build the syntaxes in LEAP that enable the calculation of changes in capital costs for each technology type along with changes in cumulative capacity and in learning rate value of the technology for each learning phase.

The capital cost of electric power technology in a specific year is calculated using the following formulas (Kim et al., 2012):

$K_t = K_c \left(\frac{C_t}{C_0}\right)^{\beta}$ and Eq. 3.9

$\mathrm{LR} = 1 - 2^{\beta}$, Eq. 3.10

where K_t denotes the capital cost in year t, C_t is the cumulative capacity until year t, C_0 is the capacity in the base year, and β is the positive learning parameter (learning index), which characterizes the inclination of the learning curve, and LR is the learning rate.

The shapes of learning curves for different energy technologies depend on two factors: initial learning rates and the speed of their change. To initialize the learning curve model, I retrieve the learning rate values for electric power technologies from Rubin et al. (2015) and Heuberger et al. (2017), (see Appendix 3.A). Further, with respect to the speed of learning, I assume four learning phases throughout the time horizon of this study where the learning rate of each electric power technology decreases with every phase, as shown in Table 3.1. This assumption refers to the WEO model 2016, which assumes reductions in the capital costs of renewable energy over time. WEO distinguishes the capital costs in four–time steps: 2015, 2020, 2030, and 2040 (OECD/IEA, 2017). The learning curve of solar PV, as the results of its substantial deployment along the time horizon of this study, is depicted in Appendix 3.B (Fig. 3B.1).

Table 3.1: Assumptions of learning rates of electric power technologies 2016–2050.

Technology	**REN–Low LR scenario[a]: Low value of the initial learning rate**				**REN–Medium LR scenario[b]: Medium value of the initial learning rate**				**REN–High LR scenario[c]: High value of the initial learning rate**			
	2016–2020	**2021–2030**	**2031–2040**	**2040–2050**	**2016–2020**	**2021–2030**	**2031–2040**	**2040–2050**	**2016–2020**	**2021–2030**	**2031–2040**	**2040–2050**
Solar PV	10.0%	7.1%	4.0%	1.6%	23.0%	16.3%	9.1%	3.7%	47.0%	33.4%	18.7%	7.7%
Wind Turbine	−11.0%	−7.8%	−4.4%	−1.8%	12.0%	8.5%	4.8%	2.0%	32.0%	22.7%	12.7%	5.2%
Biomass	0.0%	0.0%	0.0%	0.0%	11.0%	7.8%	4.4%	1.8%	24.0%	17.0%	9.5%	3.9%
USC Coal	5.6%	4.0%	2.2%	0.9%	8.3%	5.9%	3.3%	1.4%	12.0%	8.5%	4.8%	2.0%
NGOC	10.0%	7.1%	4.0%	1.6%	15.0%	10.7%	6.0%	2.4%	22.0%	15.6%	8.7%	3.6%
NGCC	−11.0%	−7.8%	−4.4%	−1.8%	14.0%	9.9%	5.6%	2.3%	34.0%	24.1%	13.5%	5.5%
Hydro	1.4%	1.0%	0.6%	0.2%	1.4%	1.0%	0.6%	0.2%	1.4%	1.0%	0.6%	0.2%
Nuclear	−6.0%	−4.3%	−2.4%	−1.0%	−1.0%	−0.7%	−0.4%	−0.2%	6.0%	4.3%	2.4%	1.0%

Note: The learning rates for the first phase (2016–2020) is based on Rubin et al. (2015). For the other phases, I estimate learning rates based on data from OECD/IEA (2017)

[a]The initial learning rates (LR), i.e., the LR values in the first phase refer to the lowest values in Rubin et al. (2015) and assumption on the low LR value for nuclear in Heuberger et al. (Heuberger et al., 2017)

[b]The initial learning rates (LR), i.e., the LR values in the first phase refer to the mean values in Rubin et al. (2015) and assumption on the medium LR value for nuclear in Heuberger et al. (Heuberger et al., 2017)

[c]The initial learning rates (LR), i.e., the LR values in the first phase refer to the highest values in Rubin et al. (2015)

3.3.3. Future Scenarios

I design five scenarios for the future development of the Java-Bali power system. The first one is the reference scenario, which assumes the continuation of the present technology mix in the Java-Bali power system. The other four are scenarios for meeting the NEP's NRE targets.

The NEP 2014 proposes ambitious NRE targets for increasing the role of renewable energy. The NRE targets relate to two stages. In Stage 1, by 2025, the share of NRE should be at least 23% of the national energy mix, which refers to the total domestic energy use coming from various sources. In Stage 2, by 2050, the share of NRE should be at least 31% of the national energy mix. NEP also mentions that the economic aspects of renewables are taken into consideration in achieving its targets (Government of The Republic of Indonesia, 2014). Furthermore, NEP also considers nuclear as alternative energy to meet its NRE targets, although it is the last option after maximizing the use of renewable energy sources.

This chapter assumes that 23% and 31% of NRE targets are applied to the power sector's energy mix. Accordingly, this chapter analyzes four scenarios for maximizing the use of renewable energy —as mandated by NEP— in the context of the Java-Bali power system and assess their impacts on costs and CO_2 emissions. The LEAP optimization method is employed to analyze the least-cost options of meeting the NRE targets with and without technological learning. The assumptions for each scenario are as follows:

a. *Reference scenario (REF)*: The reference scenario assumes a continuity of fossil-fuel-based power generation in the Java-Bali power system. Hence, the technology mix in the future is expected to be equivalent to the present situation. The main characteristics of this scenario are as follows:
   - Deployment of technology is limited to conventional technologies that have been deployed up to 2015, mainly CFPPs

- Renewable capacity expansion only limited to geothermal and hydro, as they are the only renewable technologies that existed in the base year
- No limitation on the domestic fossil fuels uses
- Geothermal and hydro expansions are dependent on their availability (potentials) in the Java and Bali islands
- No specific target is set for renewable energy deployment
- No technological learning is considered

b. *Renewable energy scenario (REN)*: In the renewable energy scenario, the NRE targets are taken into consideration when projecting the power system expansion. Besides hydro and geothermal that already operate in Indonesia, three types of renewable energy are added over the time horizon of this study: solar, wind, and biomass. Moreover, in line with NEP, nuclear is considered a new technology to be added after maximizing renewable energy uses. This scenario includes the following characteristics:
   - The capacity expansion aims at achieving the NRE targets. Thus, the NRE targets are set as constraints in the model
   - The types of technology that are considered for future capacity expansion include USC coal, NGCC, NGOC, HEPP, geothermal, wind power, biomass, solar PV, and nuclear
   - The renewables' capacity expansions are dependent on their availability (potentials) in the Java and Bali islands
   - LEAP will choose the types of technology to be employed based on costs and the set objectives
   - No technological learning is considered

In addition, I suggest three variations of the REN scenario, which vary in the initialization of technological learning for electric power technologies. I consider the learning rate of not only renewable energy technologies but also of non-renewables. Following the setup of ETL in Section 3.3.2, I assume the technological learning for all energy technologies occurs in four phases. LEAP is run with ETL, assuming three different initial values for the learning rate: low (REN–low LR in Table 3.1), medium (REN–medium LR in Table 3.1), and high (REN–high LR in Table 3.1).

(i). *Renewable energy scenario with low learning rate (REN–low LR):* the initial learning rate values refer to the minimum learning rate values (REN–low LR in Table 3.1).

(ii). *Renewable energy scenario with medium learning rate (REN–medium LR):* the initial learning rate values refer to the mean learning rate values (REN–medium LR in Table 3.1).

(iii). *Renewable energy scenario with high learning rate (REN–high LR)*: the initial learning rate values refer to the maximum learning rate values (REN–high LR in Table 3.1).

3.3.4. Data

Most of the model input data were collected from PLN and governmental reports, rather than relying on default data provided by LEAP. Therefore, this dissertation represents the actual characteristics of the Indonesian power system, making policy projections more reliable. Table 3.2 presents the model input parameters and their sources. The Java–Bali electricity demand projection for 2016 through to 2025 is based on RUPTL with an annual average of 7.3% (PLN, 2017b). Meanwhile, the demand growth projections for 2026 onwards refer to IEO 2014 with an annual average of 5.6% from 2026 through to 2040 and 4.3% from 2041 through to 2050 (DEN, 2014). The transmission and distribution losses data come from RUKN 2015–2034, which estimates a reduction from 8.5% in 2015 to 7.9% in 2030 onwards. The planning reserve margin is set at 35%, in accordance with the RUKN criteria (KESDM, 2015).

Table 3.2: Summary of model input parameter

Input Data	Value	Source
Annual demand growth 2016–2050	4.3% – 7.3%	Refers to the RUPTL and IEO estimates (DEN, 2014; PLN, 2017b)
T&D losses	7.9% – 8.5%	Refers to the draft RUKN estimates (KESDM, 2015)
System load shape	Appendix 2C	Based on hourly demand data recorded by P2B (P2B, 2016b)
Reserve margin	35%	Refers to the RUKN criteria (KESDM, 2015)
Environmental parameter	Per technology	The IPCC Tier 1 default emission factors, embedded in the LEAP's technology database (Heaps, 2017)
Discount rate	12%	The discount rate used by PLN (JICA, 2010)

The energy load shape in LEAP is drawn based on the hourly load data of the Java-Bali power system (see Appendix 2C, Fig. 2C.1). In this dissertation, the LEAP model considers the Java-Bali's load characteristics by dividing the demand in a year into 48 time-slices, which represent four variations for each month. This approach is based on historical load characteristics where there are four main variations in electricity demand, which occur during the day, night, weekend, and weekday.

The technological characteristics data of existing power plants are collected from PLN. Meanwhile, the characteristics of newly added technologies, including USC coal, biomass, wind turbine, solar PV, and nuclear power, were retrieved from various studies (see Table 3.3). Most of the technology costs assumptions are taken from the RUPTL cost data (PLN, 2017c), complemented with Indonesia Energy Outlook (DEN, 2016b), ACE (2016), OECD/IEA (2017), and the IEA & NEA (2015). The fuel costs data for coal and natural gas were retrieved from the PLN Statistics 2015 (PLN, 2016d), while nuclear and biomass fuel costs data were taken from IEA and ASEAN Energy Centre studies (ACE, 2016; IEA and NEA, 2015), respectively. For renewable, I assume that the publicly available data of the Indonesian renewable energy potential (Chapter 1, Table 1.2) can be exploited over the time horizon of this study without any constraints.

Furthermore, since NEP lists nuclear as the least preferred option for meeting the NRE targets, I assume that nuclear will be deployed for the first time in 2035 when all renewable energy potentials have mainly been exploited. Coal, nuclear, and biomass power plants are expected to cover the baseload, while natural gas and hydropower plants are expected to cover the peak load. With regard to the supply characteristics of intermittent renewable power plants (wind and solar), I specify exogenously capacity addition for hydro-pumped storages as well as set a minimum amount of natural gas power plant to be added each year to balance the intermittent renewable energies.

Table 3.3: Characteristics of technologies in the Java-Bali LEAP model

Technology	Lifetime (years)[a]	Efficiency (%)[a]	Maximum availability (%)[b]	Capacity credit (%)	Capital cost (2015 US$/kW)[a]	Fixed OM cost (2015 US$/kW)[a]	Variable OM cost (2015 US$/MWh)[a]	Fuel cost[c] (2015 US$)
USC coal	30	40	80	100	1400	31.3	2	51.8 US$/ton
NGCC	25	55	80	100	800	19.2	1	7.6 US$/MMBTU
NGOC	20	36	80	100	700	18	1	7.6 US$/MMBTU
Hydro	50	100	41	51	2000	6.6	1	–
Mini hydro	25	100	46	58	2400	6.6	1	–
Hydro P/S	50	95[b]	20	25	800	6.6	1	–
Geothermal	25	10[d]	80	100	3500	30	1	–
Solar PV	20	100	17	22	2069[e]	24.8[e]	0.4[b]	–
Wind power	20	100	28	35	2200	44[d]	0.8[b]	–
Nuclear	40[f]	34	85[g]	100	6000	164[d]	8.6[g]	9.33 US$/MWh[f]
Biomass	20[h]	35[d]	80	100	2228[d]	78[d]	6.5[b]	11.67 US$/ton[h]

[a]PLN (2017b) [b]DEN (2016a); [c]PLN (2016c); [d]OECD/IEA(2017); [e]ACE(2016); [f]Rothwell & Rust (1997); [g]IEA & NEA (2015); IRENA (2012b).

3.4. Results

The LEAP model calculation of the demand growth (Eq. 3.1) results in 305 TWh of electricity demand in 2025, doubling values recorded in 2015. Furthermore, in 2050, it increases up to 1,068 TWh—over threefold of those in 2025. The total electricity supply calculated by the LEAP model is higher than the projected electricity demand, as the electricity generation module also needs to compensate electricity losses in the T&D networks (Eq. 3.2). The following sections discuss the results of five scenarios for the Java-Bali power system's expansion to satisfy the projected future demand.

3.4.1. Reference scenario (REF)

In the REF scenario, with the business as usual technology composition, the coal capacity is added expansively over the time horizon of the simulation, followed by natural gas (see Fig. 3.1). Consequently, the electricity generation mix in the Java-Bali power system is dominated by coal. In total, fossil fuels (coal and natural gas) account for 92% and 94% of electricity supply in 2025 and 2050, respectively. Interestingly, renewable energy share reduces from 8% in 2025 to 6% in 2050 despite the full utilization of geothermal and hydro potentials of the Java-Bali islands. Therefore, the electricity generation mix in REF (Fig. 3.2) is far from what is expected by NEP. These results indicate that it is not possible to increase renewable energy share if the sector is to rely on geothermal and hydro alone without exploiting other types of renewable energy.

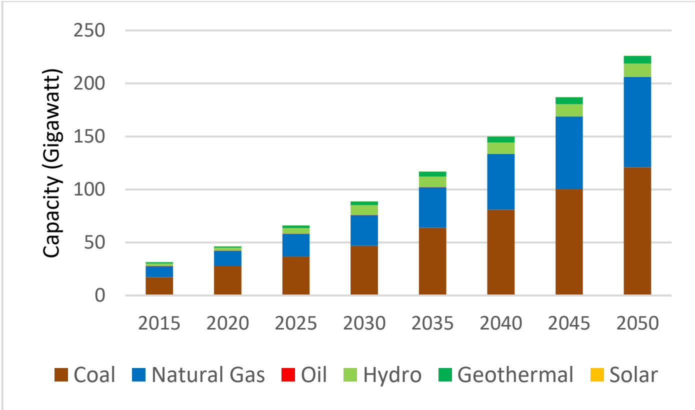


Fig. 3.1: Installed capacity, REF scenario

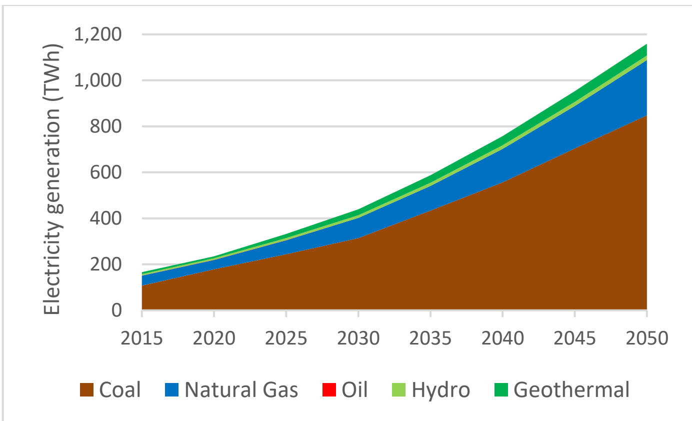


Fig. 3.2: Electricity generation mix, REF scenario.

3.4.2. Renewable energy scenario (REN)

The total power generation capacity of the Java-Bali power system reaches 69.6 Gigawatt (GW) at the end of NEP's Stage 1 (2025) under the REN scenario without technological learning (Fig. 3.3). In this scenario, the renewable capacity expands up to 15.2 GW—a nearly twofold increase compared to REF. Accordingly, there is a 22% decrease in coal capacity. During the NEP Stage 2 period in the REN scenario, the system's capacity expands further, reaching 244.4 GW in 2050. Interestingly, nuclear capacity is added significantly during this time. It is first installed in 2035 and adds up to 22 GW by 2050. In the same year, renewable capacity reaches 41 GW—threefold of that in REF.

Looking more closely into the electricity generation mix, the total electricity generation in 2025 and 2050 is 332 TWh and 1159 TWh, respectively (Fig. 3.4). Renewable energy accounts for 23% of the Java-Bali electricity generation mix in 2025, compared to 8% in REF. Hence, the NRE target Stage 1 is achieved solely by exploiting renewable energy. However, in 2050, renewable energy share constitutes only 17.3% despite full utilization of hydro, geothermal, and biomass potentials (Fig. 3.4b), which is below the NRE target Stage 2. This gap is filled by nuclear, which accounts for 14.2% of the Java-Bali electricity generation mix. These results imply that the least-cost option to achieve the NRE target Stage 2, assuming no changes in relative costs of energy technologies, is to combine renewables and nuclear. However, this scenario neglects technological learning, whereas most of these technologies become more cost-effective over time.

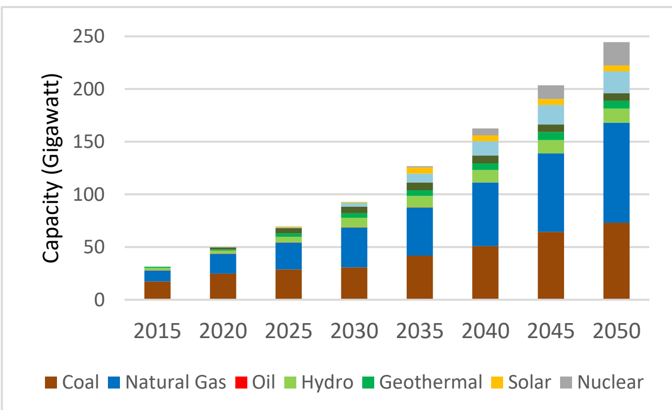


Fig. 3.3: Installed capacity in REN scenario, no technological learning

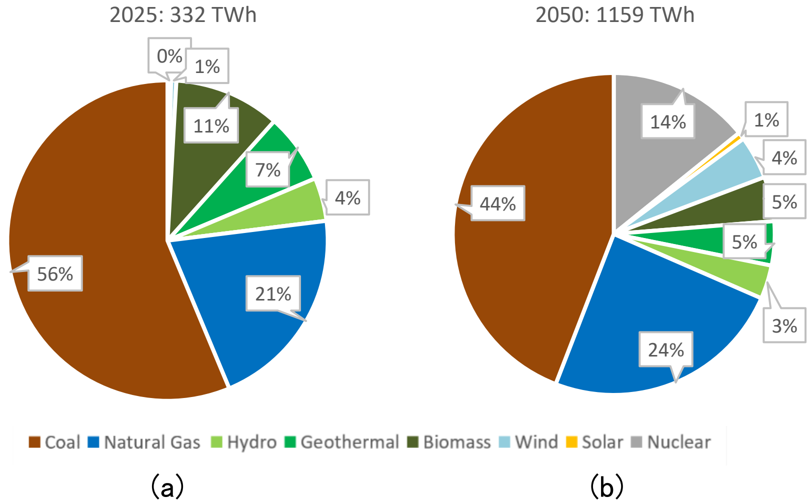


Fig. 3.4: Electricity generation mix in REN scenario, no technological learning

The following sections discuss the results of the alternative REN scenarios, which take into account the learning curves of both renewable and non-renewable technologies. In these scenarios, the capital costs of electric power technologies change along with their increased capacity depending on their learning rates.

3.4.2.1. Renewable energy scenario with low learning rate values (REN-low LR)

REN-low LR scenario assumes the minimum value of the learning rate of each technology in Phase I, which evolves throughout the other phases. The results indicate that there is a significant change in the 2025's electricity generation mix when compared to REN (Figs. 3.5a vs. 3.4a). Solar now accounts for 6% of the electricity generation mix, partially replacing biomass and geothermal, in contrast to 1% in REN. It implies that in the early phase of technological learning, even in its minimum learning rate value, solar becomes competitive with other renewables. Furthermore, the natural gas share slightly increases as compared to REN, compensating a slight reduction in coal.

These changes are seen substantially by 2050. The share of nuclear and wind power present in REN is replaced by solar (compare Figs. 3.5b and 3.4b). The solar share is now 18%, which also slightly replaces the coal share. Hence, this result suggests that when the minimum learning rate values for all technologies are considered, solar becomes more economically attractive compared to other technologies. Remarkably, even under the most modest assumptions regarding technological progress, solar proliferates from less than 1% to become the third most used energy source after coal and natural gas. A reasonable explanation could be that, in this scenario, the initial learning rate of solar PV (10%) is the highest, compared to those of nuclear (−6%), wind power (−11%), and coal (5.6%). This also explains why nuclear and wind power hardly appear in the 2050's electricity generation mix.

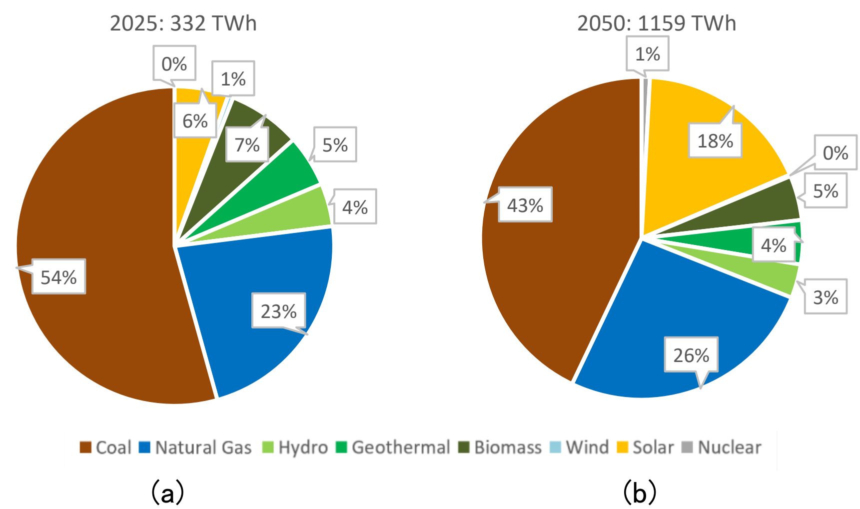


Fig. 3.5: Electricity generation mix in REN-low LR scenario, technological learning occurs at the minimum pace

3.4.2.2. Renewable energy scenario with medium learning rate values (REN-medium LR)

When the medium learning rate value for each technology is applied, a significant change is also seen in the 2025's electricity generation mix (Fig. 3.6a) as compared to REN. Renewable energy is now shared between biomass (7%), solar (6%), geothermal (5%), hydro (4%), and wind (1%). This result suggests that in the early phase of technological learning when a medium learning rate for each technology is assumed, solar and biomass compete with each other. Comparing to REN, the coal share now increases by 2%, compensating the 2% decrease of the natural gas share. Together they still support 77% of the Java-Bali electricity production while the renewables share accounts for 23% of the electricity generation mix, as targeted.

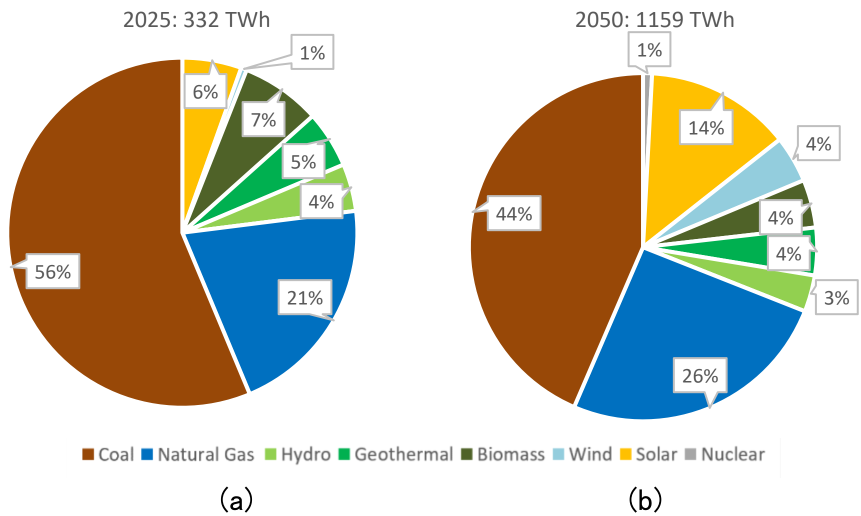


Fig. 3.6: Electricity generation mix in REN-medium LR scenario, average pace of technological learning

Turning now to the electricity generation mix in 2050, Fig. 3.6b shows that renewables account for 30% of the electricity generation, supplying nearly 350 TWh of electricity to the Java-Bali system. With an additional 10 TWh electricity supply from nuclear, NRE now constitutes 31% of the electricity generation mix, as targeted. An interesting finding reveals when comparing these results with those in REN-low LR. It can be seen that the solar share in this scenario is 4% lower than that in REN-low LR despite the fact that its learning rate in this scenario is higher than that in REN-low LR. The 4% portion is replaced by wind, which hardly appears before (Fig. 3.5b). This result indicates that in the later phases of technological learning when the learning rate values of each technology diminish, the wind power is more competitive than it is in the earlier phases.

3.4.2.3. Renewable energy scenario with high learning rate values (REN–high LR)

In the scenario with the high learning rate value for each technology, it can be seen that the 2025 electricity generation mix is comparable with those in the REN–low LR and REN–medium LR scenarios (Figs. 3.5a vs. 3.6a and 3.7a). This finding suggests that, regardless of the initial learning rate values, solar is competitive against other renewables when it is deployed in the early phases.

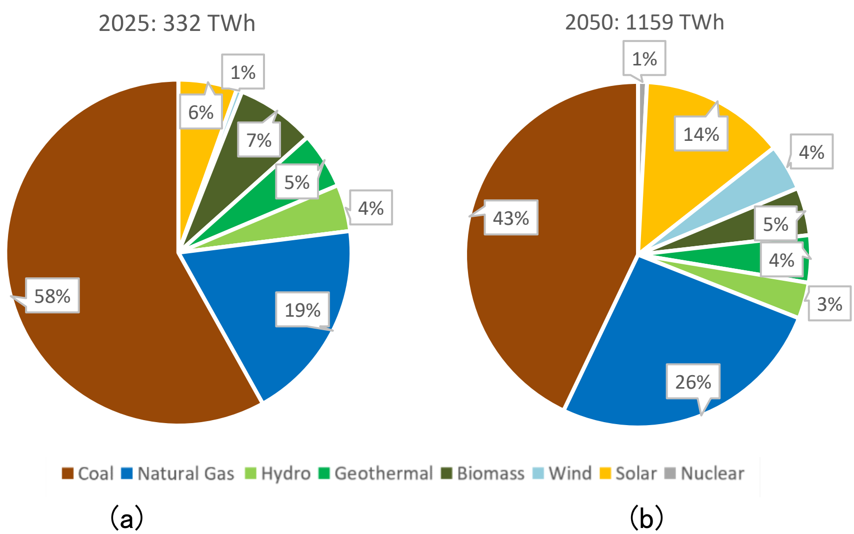


Fig. 3.7: Electricity generation mix in REN–high LR scenario, the high pace of technological learning

Results for 2050 under the intensive technological learning show that hydro, geothermal, and biomass expand up to 28.1 GW, reaching their maximum plausible capacities. Meanwhile, wind capacity adds up to 20.5 GW, almost reaching its maximum potential of 24 GW. In total, these renewables account for a 16% share of the electricity generation mix (Fig. 3.7b). After these renewables reach their maximum plausible capacities, solar and nuclear are the only options for meeting the NRE targets.

Together with 14% of solar and 1% of nuclear shares, NRE constitutes 31% of the Java-Bali electricity generation mix, satisfying the NRE target Stage 2. This is comparable with REN-medium LR, indicating that, at the medium and high initial learning rate values, all types of renewable compete with each other to achieve the NRE target Stage 2.

Comparing results from the three technological learning scenarios, several significant findings emerge. Firstly, the integration of ETL in LEAP reveals comparable results for the early phase of technological learning (2016-2025). In this phase, hydro, geothermal, biomass, and solar PV compete with each other to meet the NRE target Stage 1. Meanwhile, in the later phases, when the learning rate value of all technologies decreases, the results are slightly different between the REN-low LR scenario and the two other technological learning scenarios. While, in the former scenario, the wind power share is negligible, in the latter scenarios, the wind power is competitive with other renewables. Secondly, as far as technological learning scenarios are concerned, they meet the NRE targets mostly through renewables, barely depending on nuclear.

3.4.3. Costs

Given the pressure from the competing socio-economic priorities, including poverty eradication and other SDGs, any effort in achieving the NRE targets relies on making NRE technologies economically feasible. Hence, assessing the costs of meeting these targets is essential. Here, I compare the results of simulations from the five scenarios with respect to their total costs (Fig. 3.8). The total costs to achieve the NRE target by 2050 are 103.1 USD in REN in the absence of technology learning, which is nearly 16% higher when compared to 88.9 USD in REF.

The technological learning has an impact on the total costs, which vary non-linearly with the change in the learning pace. Results show that the total costs of REN-medium LR and REN-high LR become 4% and 10% lower, respectively, when compared to REN (Fig. 3.8). Meanwhile, the total costs of REN-low LR are 2% higher than REN, which is due to the assumptions of negative learning rates of NGCC, wind, and nuclear in this scenario (see Table 3.1). Interestingly, when the high learning rates are applied (REN-high LR), the total costs become lower than REN even by 2025. This indicates that if progress in energy technologies and their adoption intensifies, the cost reduction starts earlier, and the total costs of the expanding power sector increase at a slower rate already before 2025, making it attractive to invest in renewable energy.

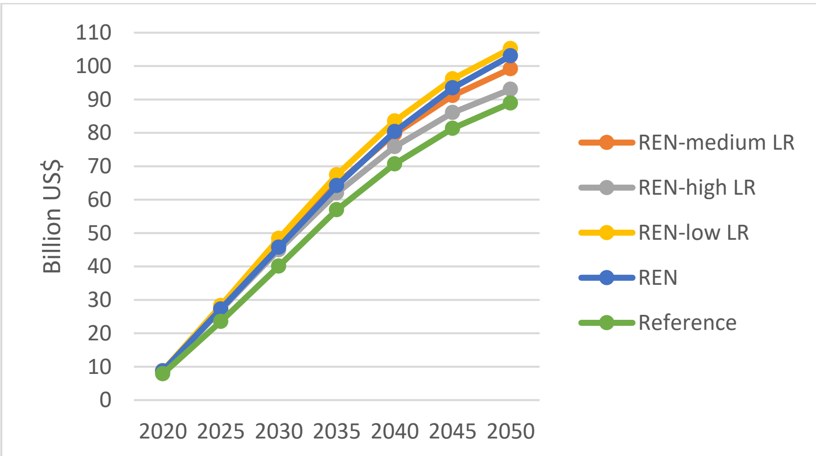


Fig. 3.8: Total costs of electricity production under reference and four renewable energy scenarios

3.4.4. CO_2 emissions

Aligned with the Paris Agreement on mitigation of climate change, the Government of Indonesia has announced its targets to reduce greenhouse gas emissions by 29% in 2030 against the business-as-usual scenario. Eleven-percent of the 29% target is allocated to the energy sector. Results indicate how much the NRE targets will contribute to the achievement of the Indonesian CO_2 reduction target (Fig. 3.9). As expected, all renewable scenarios, regardless of technological learning, result in lower emissions compared to REF. In 2030, CO_2 emissions from REN reaches 239 million-ton CO_2e, as compared to 318 million-ton CO_2e in REF. This is equal to 25% of CO_2 reduction, 6% higher than what is targeted for the power sector.

From 2030 onwards, the CO_2 emissions gap between the reference and the renewable energy scenarios becomes higher. In 2050, CO_2 emissions under REN reaches 533 million ton, compared to 798 million-ton CO_2e under REF, promising 33% emission reduction. Since the contribution from achieving the NRE targets goes beyond the country's NDC target, it can contribute to the roadmap for rapid decarbonization, which aims at achieving zero net emissions by mid-century or soon thereafter (Rockström et al., 2016).

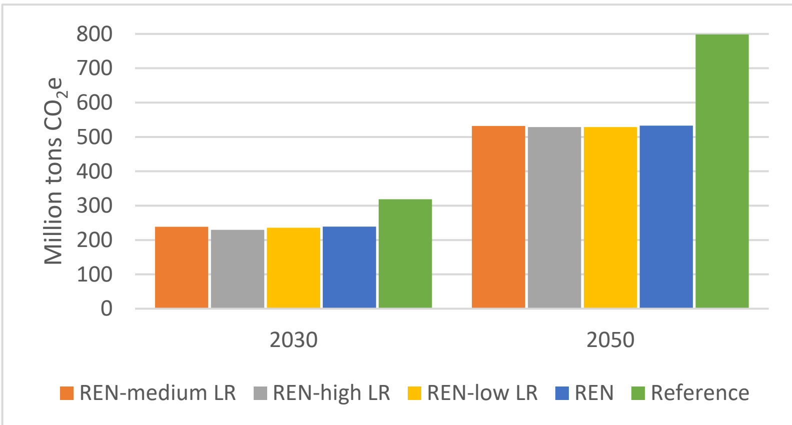


Fig. 3.9: CO_2 emissions under the reference scenario and the renewable energy scenario

3.5. Discussions

The simulation results suggest the following findings.

1). In the reference scenario, the future capacity mix reflects the situation in 2015. This results in fossil fuels continuing to dominate in the future Java-Bali's electricity generation mix. In 2025 and 2050, fossil fuels account for 92% and 94% share of the electricity generation mix, respectively.

2). The renewable energy scenario fulfills the NRE target Stage 1. In the absence of technological change, it is driven mainly by expanding geothermal and hydro capacity and by adding biomass. Meanwhile, the

NRE Stage 2 target is achieved by expanding renewables (17%) and deploying nuclear (14%).

3). The inclusion of technological learning rates significantly alters the electricity generation mix. Regardless of technological learning pace, solar PV is competitive against other renewables and nuclear. Meanwhile, in the long-run, wind power is competitive in the scenarios with medium and high learning rate values.

4). Without considering technological learning, the fulfillment of the NRE targets increases the total costs of electricity production by 15%. The incremental costs become 4% and 10% lower, respectively, when the medium and high paces of technological learning are considered, but the effect changes non-linearly with the learning rate.

The fulfillment of NRE targets provides co-benefits in terms of reducing CO_2 emissions. By 2030, CO_2 emissions decrease by 25% as compared to the reference scenario, thereby assuring the achievement of the power sector's CO_2 emission reduction target.

3.6. Conclusions

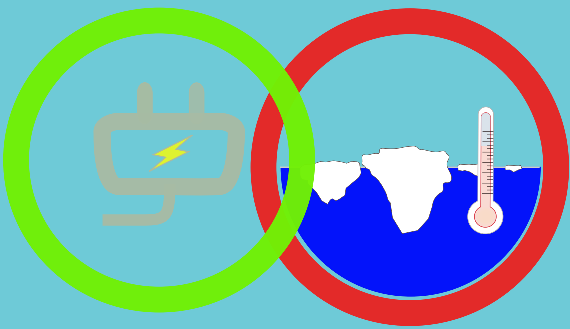
The aim of this chapter is to analyze the long-term capacity expansion in the Java-Bali power system in Indonesia, considering the national NRE targets. To the best of our knowledge, this dissertation is the first to assess the impacts of this national policy quantitatively considering technological learning. On the methodological side, this chapter makes an innovative contribution to the literature by accounting for ETL in the analysis of future electricity supply using LEAP. This chapter employs a unique detailed dataset to simulate five scenarios for capacity expansion of the Java-Bali system. The reference scenario assumes a business-as-usual electricity generation mix and no technological change. Renewable energy scenarios assess power system expansion under the national energy policy in Indonesia, using new and renewable energy targets as constraints. Furthermore, I differentiate between the standard renewable energy scenario with fixed technological costs and three renewable energy scenarios that include technological learning of electric power technologies.

Overall, the results of this chapter indicate that the incorporation of ETL into the LEAP simulation for the capacity expansion of the Java-Bali power system enables accelerating the renewable energy penetration in Java-Bali islands.

This chapter provides a framework to explore the cost-reducing effect of technological learning in the power sector using LEAP. Furthermore, it also indicates the least-cost option for the Java-Bali power system to meet the NRE targets. Looking further ahead, more detailed researches are needed to cover transmission capacity and spatial analysis of each power plant including data on the supply characteristics of intermittent energy sources, such as wind speeds and solar radiation in each region.

4

The vulnerability of the power sector to climate variability and change: Evidence from Indonesia



Abstract

The power sector is a key target for reducing CO_2 emissions. However, little attention has been paid to the sector's vulnerability to climate change. This chapter investigates the impacts of severe weather events and changes in climate variables on the power sector in developing countries, focusing on Indonesia as a country with growing electricity infrastructure, yet being vulnerable to natural hazards. This chapter obtains empirical evidence concerning weather and climate impacts through interviews and focus group discussions with electric utilities along the electricity supply chain. These data are supplemented with reviews of utilities' internal reports and published energy sector information. Results indicate that severe weather events often cause disruptions in electricity supply—in the worst cases, even power outages. Weather-related power outages mainly occur due to failures in distribution networks. Furthermore, while severe weather events infrequently cause shutdowns of power plants, their impact magnitude is significant if it does occur. Meanwhile, transmission networks are susceptible to lightning strikes, which are the leading cause of the networks' weather-related failures. This chapter also presents estimates of financial losses suffered by utilities due to weather-related electricity supply disruptions and highlights their adaptation responses to those disruptions. The findings of this chapter imply that energy policies should consider climate change adaptation in the sectoral development plans.

This chapter is published as a journal article:

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4.1. Introduction

Climate change has already greatly affected economies around the world (World Bank, 2010). Further warming of the earth by 1.5°C above the pre-industrial level would entail $54 trillion costs in damage to the global economy by the year 2100, as warned by the IPCC in its special report on 1.5°C global warming (Hoegh-Guldberg et al. 2018). More frequent and intense extreme weather events, rising temperatures, and shifting precipitation patterns are expected to impact businesses. These have brought attention to financial institutions and credit rating agencies, which now take into account climate change risks into their assessment criteria (Connell et al., 2018; Mufson, 2019). Accordingly, the new international standard, i.e., ISO 14090, has emerged to assist companies in assessing climate change impacts and developing action plans for effective adaptation (Naden, 2019).

The power sector is not immune to climate change impacts; it is affected through acute, disruptive, extreme weather events, and gradual long-term changes in climate parameters (Sieber, 2013). Extreme weather events cause damage in electricity supply infrastructures, leading to disruptions in electricity supply. Meanwhile, long-term changes in climate parameters, although not disruptive, can affect the quality and quantity of electricity supply and demand. For example, an increase in surface air temperature reduces the power output of gas turbine power plants (de Lucena et al., 2010; Bartos and Chester, 2015; Henry and Pratson, 2016) and changes in precipitation alter the reliability of hydropower (Syariman and Heru, 2011; Popescu et al., 2014).

The societal need to assure climate-resilient development has triggered scientific attention to assessing the vulnerability of the power sector to climate change. Audinet et al. (2014) discuss climate risks for the power sector and reveal the management approaches to deal with these risks taken by 12 electric utility companies operating in Canada, Taiwan, India, Australia, South Africa, and the UK. Similar studies were conducted for

Asia and the Pacific (Peter et al., 2012), the European region (Tobin et al., 2018), some areas of United States (Li et al., 2014; Vine, 2012), and Norway (Seljom et al., 2011). Other studies focus only either on the supply or demand side: for thermal power plants (van Vliet et al., 2012; Sieber, 2013; Cook et al., 2015), hydroelectric power plants (Popescu, Brandimarte and Peviani, 2014; de Lucena et al., 2009; Syariman and Heru, 2011), biofuel (de Lucena et al., 2009), solar power (Jerez et al., 2015), wind power (Pereira de Lucena et al., 2010), T&D networks (Panteli and Mancarella, 2015; Ward, 2013), and for the electricity demand (Véliz et al., 2017; Kaufmann et al., 2013).

In general, scholars agree that thermal power plants are affected by rising air ambient and water temperatures. Similarly, renewable energy, such as wind, solar, and hydropower, are also affected by climate variability and change, raising a concern on climate change mitigation and adaptation nexus. Alterations in wind speed may influence the optimal match between the wind energy source and the wind turbines power curve (Schaeffer et al., 2012). Furthermore, increasing air temperature reduces the efficiency of solar power. Moreover, extreme weather events and change in climate variables also affect the hydropower operation with uneven impacts between regions (de Lucena et al., 2009; Popescu et al., 2014; Syariman and Heru, 2011). Similarly, impacts on electricity demand vary between regions, indicating a net decrease in demand in colder regions while, on the contrary, implying a net increase in demand in warmer regions (Seljom et al., 2011; Véliz et al., 2017)

Most of these studies use simulation models to assess the projected climate change impacts on future electricity demand and supply. However, assessments of such effects based on empirical evidence are scarce. Moreover, current literature focuses on assessing one segment of the electricity supply chain: the power generation. Meanwhile, there is little information regarding climate change impacts on other segments of the power sector, which include transmission and distribution networks (Cronin et al., 2018). This chapter contributes to covering this gap in the literature on the relationship between energy and climate change by addressing the two research questions: How do severe weather events and gradual changes in climate variables affect the entire segments of the power sector? What are the current adaptation practices taken by electric utility companies?

The chapter focuses on the power sector in developing countries. It is characterized by supply shortages, aging equipment, poor performances of energy utilities, capital flow barriers, yet rapid expansions of the grid, and slow technology diffusion (Bhattacharyya, 2010; Nicolas et al., 2019). These factors reduce the reliability of the power sector and increase its vulnerability to natural shocks (Nicolas et al., 2019). As such, it is already vulnerable to present-day weather and climate, let alone future climate (Audinet et al., 2014).

Moreover, developing countries have a low adaptive capacity—socially, technologically, and financially (UNFCCC, 2007b). Hence, climate change impacts might undermine the vital role of the power sector in allowing socio-economic development that is so crucial for enabling any progress along UN SDGs in these countries. At the same time, the IPCC's fifth assessment report highlights the scarcity of literature on climate change vulnerability, impacts, and adaptation in developing countries (Clarke et al., 2014). By taking Indonesia as a case study, this chapter investigates the historical effects of severe weather events and gradual changes in climate variables on the power sector and estimates the losses suffered by electric utility companies due to weather and climate-related electricity disruptions. Furthermore, this chapter identifies adaptation measures already taken by electric utilities to deal with those disruptions. The investigation relies on extensive fieldwork in Indonesia, which comprised of interviews, focus group discussions (FGD), and reviews of utilities' internal reports and published energy sector information.

This chapter makes several original contributions to the literature. Firstly, it is among the first attempts to thoroughly examine the historical impacts of severe weather events and changes in climate variables on different segments along the power sector supply chain. Hence, this chapter provides new data that add to our understanding concerning weather and climate impacts on the production, transmission, and distribution of electricity, focusing on the direct damage costs suffered by electric utilities. Secondly, this chapter identifies measures taken by electric utilities to adapt to severe weather events and gradual climate change; therefore, it offers some important insights into firms' capacity to adapt to the changing climate. Finally, this chapter focuses on the power sector in a developing country, thereby adding to the scarce literature on climate change impacts, adaptation, and vulnerability of the sector in developing countries.

The remaining part of the chapter proceeds as follows: Section 4.2 presents the methodology; Section 4.3 elaborates the effects of weather and climate on the Indonesian power sector and discusses responses and adaptations measures taken by the electric utilities; Section 4.4 highlights the major findings; Section 4.5 draws the conclusions.

4.2. Methodology

To understand the actual effects of severe weather events and changes in climate variables on the Indonesian power sector, an extensive fieldwork was carried out in February–March 2018. An overview of Indonesia's vulnerability to climate change is provided in Appendix 4.A. The fieldwork focuses on the Java–Bali power system, covering the entire key segments of the power system: power generation, transmission, and distribution. While the power generation segment produces the electrical energy, the transmission networks, which consist of substations and transmission lines, transfer the high voltage electricity over long distances before reaching end users. Finally, the distribution networks facilitate the electricity delivery from the grid to the end user's meter at reduced, usable voltage levels.

The sources of the Indonesian electricity supply are primarily coal, natural gas, and hydropower. Hence, the investigated power generation plants comprised of major power plants of these types (Table 4.1). In total, the fieldwork covered power plants that constitute 35% of the total power generation capacity in the Java-Bali electricity grid.[10] Any disruptions that occur in these power plants, including weather and climate-related outages can cause power shortage throughout the whole Java-Bali power system. For the T&D segments, this chapter includes the entire T&D networks throughout the Java-Bali islands (Fig. 4.1).

Table 4.1: Indonesian power plants where primary data collection has taken place

Power plant	Utility	Installed Capacity (MW)	Location	Primary energy source	Data collection
Saguling	IP	797	West Java	Hydro	FGD
Cirata	PJB	1,008	West Java	Hydro	FGD
Priok	IP	1,900	Jakarta	Natural gas	Interview
Muara Karang	PJB	909	Jakarta	Natural gas	Interview
Tambak Lorok	IP	1,350	Central Java	Natural gas	Interview
Pesanggaran	IP	325	Bali	Natural gas	FGD
Suralaya	IP	3,400	Banten	Coal	Interview
Tanjung Jati B	PLN	2,640	Central Java	Coal	Interview
PJB Paiton	PJB	800	East Java	Coal	Interview
Paiton #9	PLN	660	East Java	Coal	Interview

Note: IP = PT Indonesia Power, PJB = PT Pembangkitan Jawa Bali

The fieldwork consisted of in-depth semi-structured interviews (n = 28) and five FGDs. The interviews involved key informants, holding various position levels (e.g., high and middle management levels, supervisory level, staff, and operators) of three electric utilities, who work across multiple business units (e.g., head office, load control center, transmission office, distribution office, and power plant). Meanwhile, the FGD was carried out at three power plants, one transmission office, and one distribution office.

[10]Source: own calculation based on KESDM (2017) and PLN (2017)

The respondents are employees of the utilities who are responsible for the operation and maintenance of power plants, transmission, and distribution infrastructures at different position levels.

Prior to the fieldwork, I conducted a systematic review of studies that are concerned with the impacts of climate change on the power sector. After which, I drew six questionnaires (Tables 4B.1 to 4B.6, Appendix 4.B) for guiding interviews and FGDs, which were structured differently for each target group.

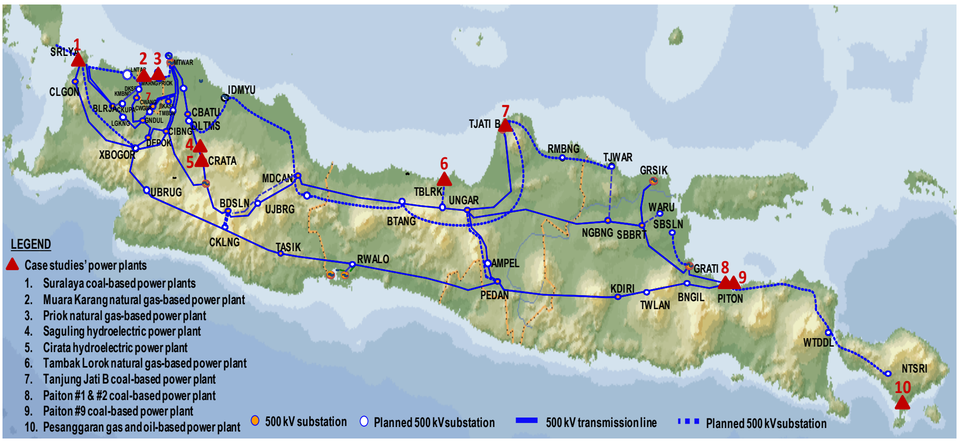


Fig. 4.1: Power plants and extra-high-voltage Java-Bali transmission networks covered by this chapter, modified from PLN (2018). While this figure depicts only extra-high-voltage transmission networks, this chapter also includes high-voltage transmission networks and low-voltage distribution networks.

The interviews and FGDs were supplemented with reviews on secondary data, which consisted of utilities' internal reports and published energy sector information (Table 4.2). These data were used to validate and triangulate the results derived from the interviews and FGDs.

The findings of the fieldwork are summarized in a matrix that presents the identified impacts of weather and climate for each segment of the power system, including estimates of financial losses suffered by the utilities and their adaptation responses. I estimate financial losses using the energy-not-supplied (ENS) data associated with the weather- and climate-related disruptions in power plants, transmission lines, and distribution networks.

The ENS data is multiplied by the average electricity tariff for a disruption event in the corresponding year. Meanwhile, there is only limited data available regarding the cost incurred by the utilities to repair the physical damages of their assets caused by severe weather events. Therefore, the chapter reports these costs per case, data permitting. There is hardly any data available regarding the probabilities of adverse events, which prohibits me from reporting the expected annual damages. Likewise, the data regarding costs associated with adaptation actions taken by the utilities is hardly available, due to proprietary data protection or lack of proper documentation.

Table 4.2: Sources of secondary data

Data	**Sources**	**Year Covered**
Disruptions in power plants	- P2B internal reports - Media covers - Suralaya CFPP's internal report	2011–2017 2007, 2008, 2011, 2013 2011–2017
Disruptions in transmission lines	- P2B internal reports - Media cover	2011–2017 2013
Disruption in distribution networks	- PLN internal reports - Media cover	2014–2015 2013
Precipitation, water inflow, and water spill	Cirata and Saguling HEPPs internal reports	Cirata: 1988–2017 Saguling: 1986–2017
The Java–Bali peak load	P2B internal report	2014
Air temperature	BMKG database center	2014
Average electricity tariff	PLN statistics	2011–2017

Note: BMKG = the Agency for Meteorology, Climatology, and Geophysics

4.3. Results: Weather and climate effects and adaptive responses of the power sector

The fieldwork reveals that weather and climate affect all segments of the power system: generation, transmission, and distribution. Disruptive severe weather events cause most of the identified effects. These include heavy wind, heat waves, lightning, and heavy precipitation, which can lead to floods and landslides. The effects of gradual long-term changes in climate variables revealed during the fieldwork include rising ambient air and seawater temperatures, changes in precipitation patterns, and sea-level rise. Tables 4.3 to 4.5 summarize findings regarding weather and climate impacts on power generation, transmission, and distribution segments of the power sector, respectively, including financial losses suffered by the utilities and their adaptation responses. The following sections elaborate findings of the fieldwork.

4.3.1. Impacts of severe weather events

4.3.1.1. Disruptions due to heavy precipitation

Flood and landslide affect electricity supply infrastructure

Heavy precipitation increases the chances of flooding in low-lying delta areas, making coastal thermal power plants and their associated T&D substations are vulnerable to flooding. According to the interviews and reviews on various documents, flooding generally results in acute situations. A notable example is a severe flood that occurred on the Northern coast of Jakarta in January 2013 that forced a 909-megawatt natural-gas-based power plant to shut down for 12 days.

Moreover, at least 546 units of an inundated distribution substation were turned off. These instances led to an estimated loss of 15.3 million USD suffered by electric utilities due to the disruptions of electricity production that month and physical damages of the power plant, transmission, and distribution equipment. The societal loss could be much more significant, considering the vital function of the power plant and its associated T&D networks as the backbone of the electricity supply to the capital city. Assessing these indirect effects are out of the scope of this fieldwork and require modeling efforts.

Besides the severe flood in 2013, PLN documentation also reveals flooding events for the years 2014 and 2015. There were 354 and 19 floods recorded, respectively, which affected the Java-Bali distribution networks. During the flooding, PLN deliberately turned off the inundated distribution substations and lines for safety reasons. The ENS due to these events reached 6.3 gigawatt-hours (GWh), with an estimated loss of nearly 0.5 million USD suffered by the utility over the two years.

<u>Heavy precipitation often causes failures in distribution networks</u>

Respondents of distribution offices and results of a review on PLN internal reports indicate heavy precipitation as the second primary cause of weather-related outages in distribution networks. By the end of 2015, the length of distribution lines throughout the Java-Bali islands was a 22,553-kilometer circuit (PLN, 2017a). These lines pass through many trees, which include community, agricultural, and forest trees. Since the majority of these lines consist of bare overhead conductors, they are sensitive to contact with tree branches or other objects. During heavy precipitation, wet tree branches along the distribution line become heavier and often touch the bare conductors causing short circuits and triggering the protection system to turned off the power. Moreover, if heavy precipitation is accompanied by severe lightning, PLN deliberately cuts off the power supply to avoid the channeling of lightning current to houses through the distribution lines' conductors.

Between 2014 and 2015, heavy precipitation caused 1,048 events of power outages in the Java-Bali distribution network. These events result in an 8.3 gigawatt-hour ENS that is equal to an estimated loss of more than 0.5 million USD over the two years. The FGD confirms that the utility is well aware of the risks posed by heavy precipitations. Therefore, preventive measures have been taken to minimize the risks (Table 4.5).

Table 4.3: Impacts of severe weather events on power generation and the utilities' adaptation responses. Source: own fieldwork.

Weather- and climate-related event	Identified impacts	Estimated utilities' financial losses (USD)	Adaptation responses
Heavy precipitation	• Soaked dry coal → reduced burning efficiency • Wet coals clogged the coal feeders → reduced power output	Suralaya CFPP, 2011–2017: 21.5 million.	• Construction of sheds to protect the coal storage area from rainwater
	• Increased river flow → more waste in the sea → impeded power plants' water uptake	Muara Karang, Priok, and Tambak Lorok NGCC power plants, 2011–2017: 15 million	• Additional work hours for waste cleaning and transportation
	• Days of heavy rainfall → high water inflow to the hydropower reservoir → reservoir's water spills → flooding downstream	N/A	• Adjust hydropower operation pattern to maintain a normal reservoir's water level
	• Flooded electricity infrastructure	Muara Karang NGCC power plant, 2013: 6.2 million	• Construction of flood control systems • Mobilization of portable water pumps for draining the water • Elevation of some areas of power plants
Heavy wind and high sea waves	Interruptions in coal shipping to CFPPs → reduced power outputs/shutdowns	Suralaya power plant, 2011–2017: 1.2 million	• Additional coal shipping fleets • Changes in the type of fleets (to a stronger and larger vessel)

Weather and climate-related event	Identified impacts	Estimated utilities' financial losses (USD)	Adaptation responses
Jellyfish inflow	Jellyfish inflow into the cooling water system of thermal power plants → reduced power output/shutdown	Paiton #9 CFPP, 2016: 21.3 million	• Installation of fishnets • Cleaning of the water intake area from jellyfish
Heatwaves	Warm ambient air temperature → reduced efficiency of gas turbine and gas/diesel engine power plants	Muara Karang NGCC power plant, 2016: 4,250	• Installation of an inlet air cooling system in gas turbine units to maintain its performance during hot ambient air temperatures
Drought	Critically low water inflow → reduced power output	Saguling and Cirata HEPPs, 2011: 51.5 million	• Adjustments of monthly operation pattern plans • Application of weather modification technology
Sea level rise	Tidal flooding → interrupted daily activities of the employees	Coastal flooding occurs periodically in Tambak Lorok and Priok power plants	• Elevation of some areas of power plants
Sea surface temperature	Warm seawater → reduced efficiency of the cooling water system	N/A	• Monitoring of seawater temperatures

Table 4.4: Impacts of severe weather events on transmission networks and the utility's adaptation responses. Source: own fieldwork.

Weather and climate-related events	Identified impacts	Estimated utility's financial losses (USD)	Adaptation responses
Lightning	• Lightning strikes → overvoltage and flashover → power failures and transmission equipment damages	2011-2017: 524,091	• Installation of the lightning monitoring system • Improvement of the lightning protection system
Heavy wind	• Power failures due to objects being blown onto the conductors or heavy wind detaching the conductors from the isolator	2011-2017: 22,139	• Repair the damaged equipment.
Flood	• Inundated substations were deliberately turned off for safety reasons	Flood in Jakarta, 2013: 9.1 million	• Elevated the flood-prone substations

Table 4.5: Impacts of severe weather events on distribution networks and utility's adaptation responses. Source: own fieldwork

Weather and climate-related event	Identified impacts	Estimated utility's financial losses (USD)	Adaptation responses
Heavy wind	• Uplifted objects damage bare conductors → power failures	2014–2015: 13.1 million	• Conduct routine inspections • Alert the 24-hour technical service teams • Apply segmentation of protection systems to avoid widespread power outages
Heavy precipitation	• Wet and heavy branches touched the bare conductors → power failures	2014–2015: 575,152	• Check and maintain distribution networks (e.g., clear distribution lines from tree branches) before the wet season come • Alert the 24-hour technical service teams
Flood	• Inundated substations were deliberately turned off for safety reasons.	2014–2015: 455,605	• Identify and elevate flood-prone substations • Replace old underground conductors that were flooded • Establish a computer application to monitor the area affected by flood-induced power outages • Establish a disaster recovery center and a special service team for post-flood recovery.
Landslide	• Heavy precipitation and heavy winds triggered landslides → damaged distribution networks	2014–2015: 9,234	• Identify landslide-prone poles • Improve poles' foundation

Heavy precipitation reduces coal quality

CFPPs generally store coals in open areas (coal yards). As heavy rainfall soaks the dry coal, the plants' burning efficiency reduces. Moreover, rainwaters generate excessive coal runoff, which in severe cases, inundates the coal yards. Respondents highlight that, subsequently, the coals turn into sticky sludge, causing clogging in the coal feeder, which prevents a continuous, reliable coal supply to the power plants' burning chambers and reduces power output. For example, the document reviews reveal that the Suralaya CFPP has experienced 544 occurrences of a power output reduction due to a clogged coal feeder during 2011-2017. Consequently, the total ENS over the seven years for this power plant alone reached 277.6 GWh, resulting in estimated losses of 21.5 million USD. The power plant reacted by building a shed in its coal yard, which currently accommodates around 10% of the coal storage area.

Heavy precipitation brings waste to power plants' water intake area

Heavy precipitation increases river flows, which in turn bring more waste into the sea. An increased volume of waste in the sea creates problems for coastal power plants. The respondents of coal- and gas-based power plants stress that small-size waste escapes water intake filters and enters the cooling water system, causing clogging in the water-circulating pump, and plugging in the condenser. Interviews and utilities' documentations point to the fact that waste has forced some units of natural gas-based plants to shut down temporarily in severe cases.

The fieldwork finds that increased waste driven by heavy rainfall affected three natural-gas-based power plants of the case studies: Muara Karang, Tambak Lorok, and Priok. A high-quantity of waste on water intake areas have caused reductions in their power outputs. In total, the ENS due to interruptions in these three power plants nearly reached 190 GWh, causing an estimated loss of 15 million USD during 2011-2017. Furthermore, the Muara Karang power plant recorded eight events of waste-related forced shutdowns over the considered seven-year period.

The massive amount of waste requires a significant number of workforce. For instance, at the Muara Karang power plant alone, the waste cleaning in its two water intake areas involves at least 80 personnel who work in shifts for 24 hours in two water intake facilities. The collected waste is transported outside the plant twice a week. However, during the peak amount of waste, daily transportation is needed, as respondents reported.

4.3.1.2. Disruptions due to heavy wind

Heavy wind damages electricity supply infrastructure

Heavy wind is by far the main threat for the Java-Bali distribution networks (Table 4.4). For example, during 2014-2015, it was responsible for 95% of the weather-related power outages. The interviews with representatives of distribution offices indicate that heavy wind can knock down trees and billboards and throw them and other objects onto the bare conductors of the distribution networks, thereby causing power outages. Multiple occurrences of heavy wind over the two years resulted in 275 GWh of ENS, leading to an estimated loss of 13.1 million USD for PLN over the two years.

Meanwhile, in the transmission networks, there were only 12 heavy-wind-related power outages recorded from 2011 through to 2017, owing to their stronger tower structure and higher conductors as compared to distribution networks. These events resulted in 0.28 GWh of ENS, which equals to 22,139 USD of financial losses over the seven years (Table 4.3). Respondents identify three reasons for the heavy-wind-related outages in T&D networks: (i) heavy wind blew tree branches or other objects onto the conductors; (ii) heavy wind caused the conductors to swing and hit the pole/tower's body; (iii) Heavy wind detached the conductors from the insulators.

Respondents of the distribution offices state some proactive measures they have taken responding to heavy-wind-related disruptions. They regularly monitor weather forecasts; in case a heavy wind is approaching, they alert its 24-hours technical service teams and ensures sufficient people and materials available to overcome any damage that may occur when the heavy wind comes. Beside corrective measures, they also include preventive measures by conducting inspections on its distribution networks. The inspection includes cutting tree branches that could potentially harm the distribution network when heavy wind occurs. The control also checks and maintains pole stands to ensure that they are supported by an adequate foundation. In case a power outage occurs due to severe weather, they prevent widespread power outages by applying the segmentation of the distribution's protection system. Meanwhile, the response of transmission offices to heavy-wind-related disruptions so far has been on the investigation of the cause of power transmission failures and repairing the damaged equipment without any ex-ante adaptation actions.

Heavy winds also cause damages to power plants' facilities. For example, in 2007, a heavy wind slammed two coal ships, causing them to crash into the coal loading facility of the Tanjung Jati B CFPP. Consequently, the coal unloading facility did not function for two weeks, which resulted in a critical stock of fuel coal in the power plant, forcing the plant to shut down for some time. Furthermore, in March 2017, a heavy wind lifted the roof of the coal yard's shed of Paiton #9 CFPP and crooked some of the shed's pipes. Respondents state that nothing has been done in terms of improving the resiliency of infrastructure against the severe weather.

Heavy wind disrupts the fuel-coal stock

The interviews with representatives of head office and coal fired-power plants reveal that heavy wind and high waves in the Java Sea affect coal transportation to the Java island. The CFPPs sited in Java rely on sea-shipped coals from coalmines of other islands. During heavy winds, coal loading and unloading activities are prohibited, which causes a longer waiting time for coal deliveries. Moreover, high waves in the Java Sea, which often occur during the wet season, prevent coal barges from cruising. These circumstances jeopardize the stock of coal at CFPPs, which often lead to reductions in the plants' power outputs. For instance, in 2007, Tanjung Jati B CFPP experienced critical fuel-coal stocks twice –in March and December– due to severe weather in the Java Sea. The media reported forced shutdowns of the CFPP for days due to the disruptions in coal supply (Damayanty, 2008; 'Tanjung Jati', 2007). Consequently, the costly oil-fueled power plants were operated to substitute such capacity loss in the Java-Bali grid, causing an additional cost of 1.6 million USD per day during those critical days in March and December 2007 (Detikfinance, 2007).

Recent data from the fieldwork show that severe weather events in the Java Sea continue posing threats to the security of coal supply for CFPPs. In December 2017, the average coal stock of Tanjung Jati B was only enough for 13 days of operation, which was halved of the planned stock of 25 days. By the end of January 2018, the stock was only enough for three days of operation, leaving the plant vulnerable to a forced shutdown. Similarly, the average coal stock of PJB Paiton power plant in January 2017 reached a critical point, i.e., less than three days. In Suralaya CFPP, the disturbances in coal stock between 2011 and 2017 resulted in an estimated loss of 1.2 million USD in total.

As per the interviews, to avoid critical fuel-coal stocks during severe weather events, CFPPs responded by revising their contracts to add the number of coal shipments and to use stronger and larger vessels.

4.3.1.3. Heatwave effects on electricity supply and demand

<u>Heatwave reduces generation capacity of natural-gas-based power plants</u>

The heatwave is particularly a concern for natural-gas-based power plants. Interviews with representatives of these power plants indicate that warm air temperatures affect the gas turbines and gas engines of the power plants. The operation of this type of power plant requires ambient air for compressor intake, which is then pumped into the burning chamber. The higher the air ambient temperature, the lower the air density and, hence, the burning efficiency, which subsequently reduces power outputs.

Utilities recorded disruptions in several natural-gas-based power plants attributable to heatwaves. On March 17, 2015, two units of gas turbines in the Muara Karang power plant reduced their power outputs by 14% and 17% each due to the hot temperature outside, which was measured at 35°C. Similarly, on May 3, 2016, two other units of the same power plant experienced a reduction in power output by 3% of their capacity due to high ambient air temperature. The latter caused an estimated loss of 4,250 USD suffered by the power plant on that particular month alone. Another case that is worth mentioning is a disruption that occurred in the Pesanggaran power plant. During the fieldwork visit on March 1, 2018, the ambient air temperature was 33°C. At this temperature, the engine could not deliver the optimum power output. The screen in the control room shows "automatic derating" notification with an explanation of the cause: a high ambient air temperature. The information means that the engine automatically reduces its output due to high air temperature.

The FGD and interviews reveal that reductions in power outputs due to warm-ambient air temperature have not been a substantial issue for the Java-Bali electricity grid as a whole. However, for the Bali subsystem, it was a significant problem in 2010 due to its limited power generation capacity then, while the power transfer from the Java subsystem was constrained by a technical barrier in the transmission networks. Hence, it was essential to optimize power output from local plants in Bali. Therefore, the Pesanggaran power plant in Bali adapted by installing an inlet air cooling system in its gas turbine units to maintain the machine performance during hot temperatures.

Heatwave increases electricity use

Respondents confirm an increase in electricity demand during hot temperature days. An IP internal report reveals that in the Bali subsystem alone, the difference in peak demand between hot and cold days/nights can reach 100 MW—around 12% of the peak demand in 2017. Hence, a surge in electricity demand due to warmer temperature directly affects the power system, as the system should be able to accommodate any surge in electricity demand. In the long-term, an increased mean temperature will require a more substantial investment in power generation, transmission, and distribution networks to cope with the increased energy use (MWh) and higher peak demand (MW).

4.3.1.4. Disruptions due to lightning strikes

Respondents from the transmission offices point to lightning strikes as the leading cause of weather-related disruptions in high-voltage transmission lines. According to the interviews, a lightning strike can induce an overvoltage on transmission lines and cause a flashover, which results in power failures, and damages power transmission equipment. Therefore, transmission lines generally equipped with shield wire and insulation to protect them from a lightning strike (Table 4.3). However, lightning strikes that occur too frequently can reduce the lifetime of the protective equipment, causing an increase in transmission's failure and its maintenance costs. The fieldwork reveals 107 events of lightning strike-related power outages in transmission networks throughout the Java-Bali power system during 2011-2017. The total ENS during the same period was 67 gigawatt-hour, which is equal to 0.52 million USD over the six years.

Being aware of the risks posed by lightning, PLN established a lightning monitoring system, which derives the data regarding the occurrence of lightning strikes in the transmission network areas. The monitoring system produces a lightning density map and data regarding the exposure of lightning to the transmission network. The transmission offices compare these data with the disruption events in the transmission networks to conclude whether a disruption occurred due to lightning or something else. In case lightning strikes are found responsible for any disruptions in a specific transmission line or substation, PLN improves the lightning protection facilities at this location. Such improvements include the installation of transmission line arresters and the improvement of grounding systems and earth wire conductor materials. PLN also uses lightning data as a consideration for the planning of the transmission network's development.

4.3.1.5. Disruptions due to jellyfish inflows

This chapter adds the 'jellyfish outbreak' into the extreme category because, in this context, it is associated with a drastic seawater temperature change (Rafiq, 2016). Jellyfish inflow on thermal power plants is an extreme event that occasionally occurs on the Northern coast of Java. According to interviews, jellyfish often slip off screening facilities for the inlet water, causing a problem in the cooling water system of CFPPs. A severe jellyfish inflow can cause a reduction in power generation capacity or even force the power plant to shut down. For example, in April 2016, the jellyfish inflow to Paiton #9 CFPP forced the plant to shut down for 20 days, causing an estimated loss of 21.7 million USD due to ENS alone. According to BMKG, the jellyfish outbreak was triggered by an extremely cold temperature in the Australian sea, forcing jellyfish to migrate to the North Java Sea (Rafiq, 2016).

The first emergency response to the jellyfish inflow at that time was cleaning and spraying the traveling screen, flushing the inlet of water intake, and installing fishnet on the water intake canal. However, these responses were not enough to block the jellyfish inflow, and in the end, the plant was forced to shut down. After the plant was shut down, manual cleaning of the water intake canal was carried out, involving 90 personnel, including divers. The damaged equipment was also repaired. The shutdown of Paiton #9 CFPP caused a power supply shortage in the Java subsystem. Consequently, the Java subsystem had to import the expensive oil-based electricity from the Bali subsystem.

Jellyfish inflow also occurred in the water intake facility of Tanjung Jati B CFPP. The jellyfish inflow blocked the water uptake of the cooling water system, which eventually caused reductions in power output. From 2011–2017, there were 11 occurrences of jellyfish inflow that affected the

Tanjung Jati B electricity productions. The problem was generally solved within 0.5 to a few hours. The estimated losses suffered by Tanjung Jati B due to the jellyfish-induced reductions in the plant's energy production reaches 0.3 million USD over the seven years. Apart from the jellyfish migration from the Australian sea, the jellyfish outbreak can be attributed to among others, a warmer sea temperature (Purcell, 2005; Aljbour et al., 2019). So far, the power plant has taken ex-post measures such as installing fishnets and cleaning the water intake facility from the jellyfish.

4.3.2. Impacts of gradual changes in climate variables

4.3.2.1. Changes in precipitation pattern affect hydroelectric power plants

The FGDs with representatives of two hydropower plants conclude that changes in precipitation patterns affect the hydropower operation already today, raising concerns about future climate conditions. My analysis based on the power plants' data confirms the strong correlation between precipitation, water inflow to the reservoir, and electricity production of hydropower (Figure 4C.1 and 4C.2 Appendix 4.C). The primary climate-induced challenge for hydropower is, therefore, to manage the situation during extreme wet and dry seasons. For example, reductions in generated capacity due to long-lasting drought were observed in 1997, 2003, 2006, and 2011. In 2011 alone, both Saguling and Cirata HEPPs only utilized 87% and 75% of their design capacities, respectively, resulted in 51.5 million of ENS-related financial losses. Furthermore, in September 2011, they were only able to operate half of their capacity and only to serve the peak demand (Musim Kering, 2011).

Table **4.6**4.6 compares the energy generated in extremely dry years with their design capacities and estimates the ENS due to the lack of water.

In contrast, days with heavy rainfalls result in high water levels of the reservoirs. This situation gives a positive impact enabling the HEPPs to produce electricity at their maximum capacity. However, excessive water inflow can lead to water spills, which should be avoided as much as possible as it can increase the downstream flow and cause flooding. For example, heavy precipitations along the Citarum watershed in March–April 2010 led to a significant inflow to the two reservoirs and also to another reservoir of the same watershed, causing lasting downstream flooding (Syariman and Heru, 2011). Fig. 4.2 presents historical water levels and energy spills of the Saguling reservoir, indicating that peaked water inflows are followed by water spills, which calculated as energy spills.

Table 4.6: Percentage of electricity production in dry years compared to design capacities. Source: own analysis

Dry years	Percentage of energy generated compared to design capacity		Total ENS for both HEPPs in GWh
	Saguling	Cirata	
1997	61%	60%	1,400
2003	81%	67%	882
2006	70%	62%	1,174
2011	87%	75%	637

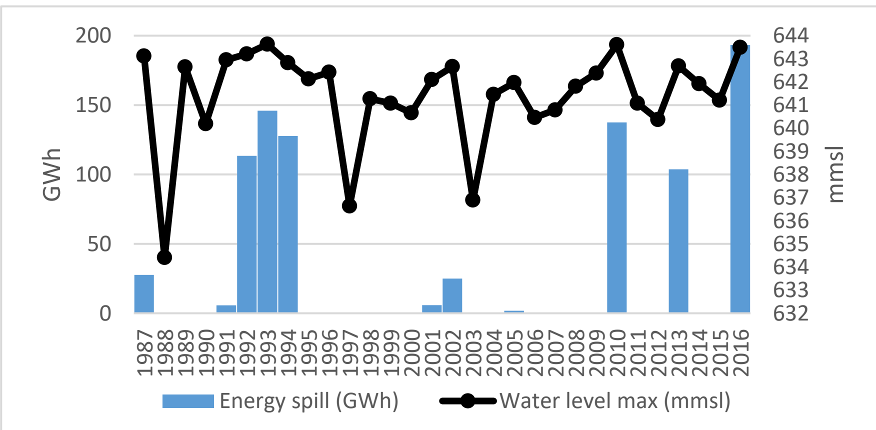


Fig. 4.2: Annual maximum water levels and energy spills: Saguling HEPP from 1987 through to 2016. Source: own fieldwork.

Both HEPPs take managerial and technological adaptation responses to address low water inflows. The former is done through an adjustment of the HEPPs' operation pattern plans. In the normal situation, Cirata and Saguling HEPPs can be called to supply electricity at any time to meet demand and to stabilize the frequency of the power system. However, during low water levels in reservoirs, they are only operated to serve the increasing energy demand at peak hours (Musim Kering, 2011). The technological response is through an application of weather modification technology that creates artificial rain, which was done in 2011 when extreme drought occurred. Meanwhile, when there is excessive water enter the reservoirs, the HEPPs should maintain the standard reservoir's water level by maximizing water use for producing electricity. However, in severe cases, water spill could not be avoided.

4.3.2.2. Warmer ambient air temperature increases electricity use

The mean annual temperature in Indonesia has increased by 0.04°C per decade between 1985 and 2015 (GERICS, 2015). As discussed in Section 4.3.1.3, the interviews indicate a rise in electricity demand during warmer temperatures. To validate this, this section analyzes the hourly load data, and the peak electricity demand data collected from P2B, relating these data to the average temperature data from 23 weather stations retrieved from the BMKG database center. As a result, a strong relationship between an increase in electricity use and air temperature rise is found (Fig. 4.3). Therefore, an increase in the mean temperature is expected to boost the average electricity consumption.

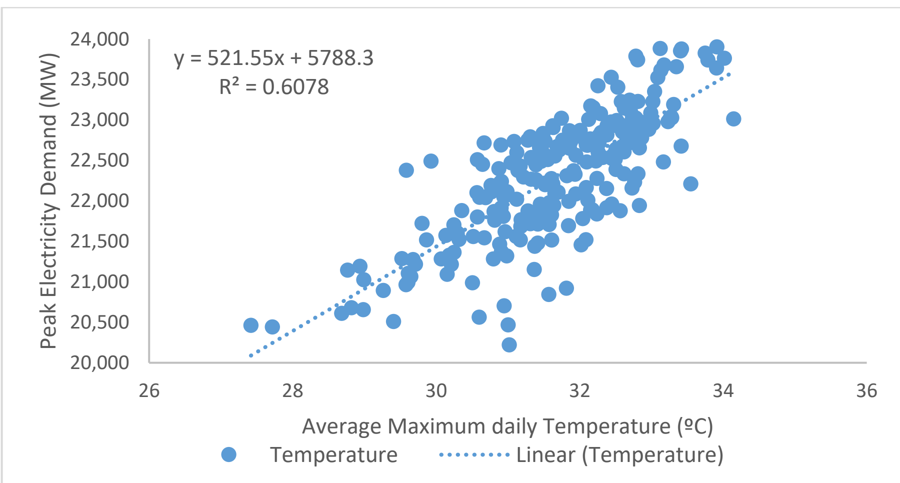


Fig. 4.3: Peak electricity demand in the Java-Bali grid as a function of maximum daily temperature: weekdays 2014. Source: own fieldwork.

4.3.2.3. Seawater temperature affects the cooling water system

The seawater temperature is crucial for coastal power plants, which rely on seawater for their cooling systems. The seawater temperature correlates with the performances of a condenser of a cooling water system. Respondents of the PJB Paiton CFPP revealed that higher temperatures resulted in higher pressures of the condenser, which, in turn, reduced the efficiency of the power plant. Thus, this section examines the relationship between the cooling water temperature and the performance of a condenser, based on the condenser monitoring data provided by PJB Paiton. The result shows a strong correlation between the cooling water temperature with the condenser pressure (Fig. 4.4). Although PJB Paiton monitors the seawater temperature data and evaluates its impact on the power plant's performance, no concrete capital or technological adaptation response has been taken.

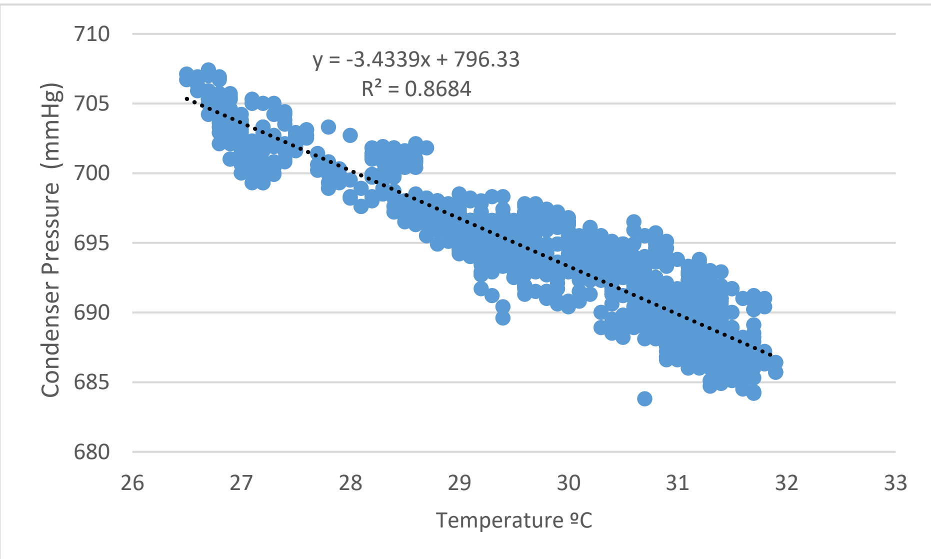


Fig. 4.4: The condenser vacuum as a function of cooling water temperature: PJB Paiton CFPP, half-hourly, December 2015. Source: own fieldwork.

4.3.2.4. Sea-level rise contributes to tidal flooding

Indonesia has recorded 2 to 10 mm of annual sea-level rise from 1993 to 2012 (USAID, 2017). Sea-level rise threatens coastal power plants and their associated T&D substations. Tidal flooding often occurs in coastal power plants, especially during high tide and heavy precipitation. For example, Priok and Tambak Lorok gas-based power plants are often hit by tidal flooding. Priok, which is located on the Northern coast of Jakarta, lies in the altitude of 0–2 m above sea level. It is a flood-prone area where nine rivers and two flood canals meet. The lower parts of the power plant have often inundated, disturbing some activities such as employees' mobility between buildings. The water inundation level is considered dangerous when it reaches 35 cm, which has occurred in 2007 and 2008. Respondents point out that tidal flooding has never caused production failure so far because the powerhouse is located on the higher altitude of the power plant area. However, in 2007, one of the Priok power plant's transformers was flooded (Fig. 4.5a). Hence, it was deliberately disconnected from the grid during the flooding for safety reasons. During the 2007 and 2008 flooding, the Priok power plant mobilized a portable water pump for draining the water. After the floods, some areas of the plants were also elevated.

Tambak Lorok power plant is located on the Northern Coast of Semarang, Central Java at the elevation of 0.75–1.5 m above sea level (IP Semarang, 2017). The sea-level rise in combination with land subsidence makes the plant vulnerable to tidal flooding and future changes in these due to climate change. The flooding occurs periodically; in fact, when the field visit was conducted in February 2018, the front gate of the plant was flooded (Fig. 4.5b). As an adaptation to this situation, the Tambak Lorok power plant constructed a flood control system, which included a polder, water sump pumps, a wall, and upgraded its drainage system to improve its resilience against seawater surge. Moreover, an additional polder is currently under construction to manage water inflow from the front side of the plant.

(a)

(b)

Fig. 4.5: Tidal flooding affects coastal power plants: Priok in 2007 (a) and Tambak Lorok in 2018 (b). Source: own fieldwork

4.4. Discussions

The findings of this chapter reveal the adverse impacts of weather and climate to the power sector, including past losses both in energy-not-supplied and in USD, and indicate the adaptation measures already taken by the actors in the Indonesian power sector.

Impacts: Severe weather events and gradual changes in climate variables affect all segments of the power sector, namely generation, transmission, and distribution. My findings suggest that, in terms of the frequency of failures, the distribution network segment is the most vulnerable to severe weather events. Meanwhile, weather-related disruptions occur less frequently in the power generation segment. Nevertheless, whenever it does happen, the magnitude is significant, knocking out power plants for days and causing tens of millions of USD in the direct damage alone. Severe weather mainly affects the fuel-coal quality and the coal stock of coal-fired power plants, and the reliability of the cooling water system in both coal- and gas-based power plants. These effects raise concerns regarding climate-resilience of fossil-fuel-based electricity production, which to date outprices green electricity options in Indonesia and forms the core of its future electrification plans. Changes in precipitation patterns also affect hydropower operation, undermining its role in serving electricity demand during peak hours. Concerning the transmission network, the primary cause of weather-related disruptions is the lightning strike. Yet, the weather-related damage in this segment is minor when compared to those in the distribution and generation segments.

Adaptation: To some extent, actors throughout Indonesia's electricity supply chain already implement adaptation actions in response to severe weather events, combining managerial and technological interventions. The technological responses include investments in flood control systems in power plants, a lightning monitoring system for the transmission networks, and an application of weather modification technology to create artificial rain to increase water inflow to hydropower reservoirs. Managerial responses include altering coal shipment contracts, increasing routine distribution network checks, and altering hydropower operation patterns. However, these adaptation responses are limited to ex-post reactions to weather- and climate-related disruptions encountered by utilities. Furthermore, the responses are fragmented rather than a part of a national strategy and focus only on assets already adversely affected. Meanwhile, a long-term strategic plan that ex-ante anticipates future climate change-related risks and systematic adaptation responses have not been considered.

4.5. Conclusions

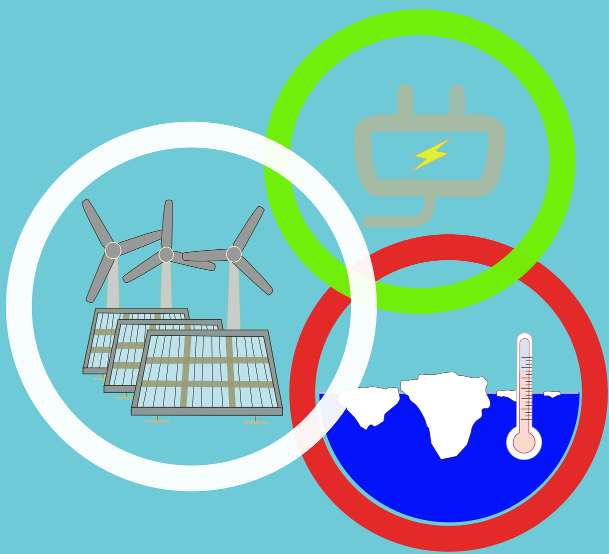
This chapter aims to systematically investigate the effects of severe weather events and changes in climate variables on the electricity supply chain, taking Indonesia as an example of a developing country where natural hazards already undermine the resilience of the power sector today. Relying on extensive fieldwork carried out in 2018, this chapter reveals which, and how severe weather events and changes in climate variables adversely affect the Indonesian power sector.

The estimation of weather-related damage to the power sector in this chapter is limited to the direct losses suffered by electric utilities, primarily including energy-not-supplied. It also includes direct economic losses from damaged assets and equipment when data permits. This chapter, however, does not account for complete economic losses due to weather- and climate-related widespread power cuts. Hence, business interruptions and other cross-sectoral impacts of hazards are out of the scope of this chapter.

This chapter contributes to the literature by providing empirical insights into the actual effects of severe weather events and changes in climate variables on the entire electricity supply chain in a developing country, both in physical and monetary terms where data permitted. Moreover, it provides unique information on the variety of the actual adaptation responses of actors throughout different segments of the electricity supply chain to severe weather events. Future research might integrate the observed and projected climate change impacts into simulations of the electricity system expansion for realizing a climate-resilient electricity system and estimating costs and benefits of adaptation of the power sector to climate change.

5

Climate change mitigation and adaptation nexus: Analysis of a low -carbon electrification scenario incorporating climate change impacts



Abstract

The power sector is in the spotlight for reducing carbon emissions. However, little attention has been paid concerning the impacts of climate change on the sector. This chapter analyzes the interplay between electrification, climate change mitigation and climate change impacts and adaptation in the power sector. Taking Indonesia as an example, this chapter integrates both climate change mitigation goals and the impacts of climate change into simulations of an Indonesian power system expansion using LEAP. First, this chapter quantifies the impacts of climate change on electricity demand and supply based on historical climate-related impacts and climate change projections. Thereafter, the quantified effects, together with renewable energy targets, then integrated into the LEAP modeling architecture. Results show a substantial alteration in technology composition driven by the joint climate mitigation-adaptation scenario compared to the reference scenario. Furthermore, there is an increase in installed capacity and electricity generation relative to the reference scenario to balance the climate-induced rise in electricity demand and to compensate for the reductions of the power-generating capacity under new climate conditions. Consequently, the total costs of electricity production increase significantly.

This chapter is based on:

Handayani, K., Filatova, T, Krozer, & Y., Anugrah, P. (2019). Seeking for climate change mitigation and adaptation nexus: Analysis of a long-term power system expansion. Applied Energy. (Under review).

5.1. Introduction

The energy sector is a significant contributor to global warming. Accordingly, most of the NDCs submitted by the UNFCCC parties include reducing emissions from this sector as their strategies to meet their pledge under the Paris Agreement (UNFCCC, 2016). However, the energy sector is also vulnerable to the impacts of climate change. Extreme weather events and gradual changes in climate variables have implications for the reliability, cost, and environmental effects of the energy supply (Schaeffer et al., 2012; Cronin et al., 2018). Therefore, it is a great challenge for the energy sector to meet their climate mitigation goals while at the same time, cope with climate change impacts. For developing countries, this challenge coincides with their vital electrification objective as they face rapid growth in electricity demand.

Significant research has addressed the decarbonization of the power sector in response to the Paris Agreement. Grande-Acosta and Islas-Samperio (2017) provide an alternative scenario to decarbonize the Mexican power sector by assessing 36 mitigation options using LEAP. Handayani et al. (2017) also employ LEAP to analyze scenarios for the Indonesian power system to meet both electrification and Paris climate goals. Dalla Longa and van der Zwaan (2017) adopt TIAM-ECN model to investigate the role of low carbon technologies in achieving Kenya's Paris climate target. A study for the Malaysian power sector was conducted by Haiges et al. (2017), which utilizes TIMES model to assess the long-term power generation options considering climate change mitigation. Lee and Huh (2017) propose a diffusion model to evaluate the impact of South Korean renewable energy policies triggered by the Paris Agreement, on the diffusion of renewable electricity. Overall, these studies indicate that the Paris Agreement is achievable but entails various consequences such as increasing costs and alterations in technology and energy mixes.

While mitigation efforts are vital, it is evident that adverse impacts of climate change affect various sectors of social-economic systems already today, and these impacts may facilitate or hinder mitigation efforts of the power sector (Cronin et al., 2018). The previously-mentioned studies pay little attention to adverse climate change impacts, and yet they are expected throughout the entire elements of the power system. On the supply side, climate change impacts include changes in water availability and seasonality of hydropower, alteration in wind speed frequency and distribution, reduction in solar cell efficiency, a decline in generation cycle efficiency and cooling water availability of thermal power plants, as well as failure and reduction in the capacity of transmission and distribution lines. On the demand side, climate change alters the balance of heating and demand patterns (Schaeffer et al., 2012; Cronin et al., 2018; Audinet et al., 2014). Neglecting these impacts can undermine efforts to decarbonize the energy sector (Cronin et al., 2018).

Furthermore, the IPCC AR5 has recognized climate change impacts and adaptation responses of the energy system as a research gap and urge their integration into the assessment of climate stabilization path (Clarke et al., 2014). This is crucial as climate change impacts could influence, among others, the effectiveness of mitigation options. AR5 also highlights the scarcity of publications regarding climate change impacts, adaptation, and vulnerability from developing countries (Field et al., 2014).

This chapter aims to address this gap in the literature by conducting a holistic analysis of a low-carbon pathway of the power sector, accounting for the adverse climate change impacts. It integrates both climate change mitigation goals and climate change impacts into modeling simulations of the Java-Bali power system expansion in Indonesia. Indonesia, an emerging developing economy with fast-rising electricity demand, embarks on a low-carbon energy system by setting out a target to increase the share of renewable energy by 23% in 2030 and 31% in 2050. This target is in line with the country's NDC to reduce 29% of CO_2 emissions from the business as usual scenario.

LEAP is used for conducting simulations of the long-term expansion of the Java-Bali power system. Prior to commencing the simulations, the impacts of climate change on the electricity demand and supply were quantified based on fieldwork in Indonesia, revealing the past consequences of climate-related events (Chapter 4) and on the secondary data of global climate change projections. The quantified effects, together with the renewable energy targets, are then converted into constraints within the LEAP optimization modeling architecture.

This chapter offers several contributions to the current literature and practice. Firstly, to the best of our knowledge, this chapter is the first to jointly consider climate change mitigation goals and climate change impacts on various elements of the power sector into simulations of power system expansion using LEAP. This chapter is novel in the sense that it explicitly links the sectoral efforts to pursue the low-carbon pathway with its adaptation to the adverse climate change impacts and fills an important gap in the literature on the climate-resilient energy sector. Secondly, this chapter adds to the scarce literature on climate change impacts, adaptation, and vulnerability of developing countries and may serve as a reference for policies facilitating a low-carbon and climate-resilient power sector.

The remaining part of this chapter proceeds as follows. Section 5.2 lays out the existing literature on modeling a power system expansion under climate change and outlines knowledge gaps. Section 5.3 describes the employed methodology, and Section 5.4 presents the results of the LEAP modeling for each scenario. Section 5.5 discusses the significance of the findings of the modeling work. Finally, Section 5.6 provides conclusions and limitations of this chapter as well as recommendations for future work.

5.2. Modeling climate change impacts on the power sector

The recognition of the power sector vulnerabilities to the effects of the changing climate is growing, as does the need to quantify these impacts, usually with the help of models. Tobin et al. (2018) investigate the impacts of climate change on four electricity supply technologies (wind, solar PV, hydro and thermal power supply) in 28 EU countries based on EURO-CORDEX regional climate model projections. Other studies focus mainly on the impacts on thermoelectric power plants. Cook et al. (2015) develop a methodology for predicting thermal power plants' risks of violating thermal pollution limits due to climate-induced drought and heatwave in the Upper Mississippi River Basin and Texas. Furthermore, van Vliet et al. (2012) analyze the impact of changes in temperature and water availability under climate change on thermoelectric power plants in the U.S. and Europe using a physically-based hydrological and water temperature modeling framework in combination with an electricity production model. Likewise, Zheng et al. (2016) investigate the vulnerability of the Chinese thermoelectric power plants to water scarcity problems by performing a high-resolution evaluation and projection of spatial vulnerability. Collectively, these studies agree that the adverse effects of changes in climate variables such as temperature and precipitation reduce the power generation capacity of thermoelectric power plants.

Meanwhile, adverse impacts of gradual changes in climate variables on wind and solar PV are found to be limited (Tobin et al., 2018; Jerez et al., 2015; Pereira de Lucena et al., 2010). Moreover, Lucena et al. (2010) and Pašičko et al. (2012) estimate an increase in wind power production under the future climate in some parts of Brazil and Croatia, respectively. Nonetheless, off-shore wind power plants may need to invest in adaptation measures against sea-level rise (Lise and van der Laan, 2015).

Results with respect to climate change impacts on hydropower are mixed. Anugrah et al. (2015) evaluate Bayang micro hydropower system in Indonesia using WEAP-LEAP models and find that climate change will reduce power production. Obahoundje et al. (2017) also employ WEAP to explore the combined effect of land use and land cover change and climate change on water availability for all demand sectors, including hydropower. The study shows contradictory results regarding the power generation between two climate change scenarios. Zhang et al. (2017) evaluate the vulnerability of hydropower of the Yangtze river basin to climate change using WEAP and also find large fluctuations in the power generating capacity. Namely, the supply increases under the high-temperature scenario and decreases under the low-temperature scenario, thereby increasing the vulnerability and uncertainties of hydropower supply systems.

Compared to other energy sources, climate change impacts on hydropower have been extensively incorporated into simulations of long-term power system expansion. Such popularity is due to the hydropower dominance in some countries, its long asset lifetime, and its apparent dependence on climate (Cronin et al., 2018). The integration of climate change impacts into simulations of a power system expansion allows analyzing their associated impacts on the power system as a whole. To mention a few studies: Lucena et al. (2010) for the Brazilian power sector, Teotónio et al. (2017) for the Portuguese power system, Arango-Aramburo et al. (2019) for the Colombian power sector, and Spalding-Fecher (2017) for the Southern African Power Pool. Overall, these studies indicate a decline in hydropower generation under climate change, although the declining percentage is marginal is some countries while significant in others. Consequently, extra capacity from other energy sources is required to compensate for the lack of reliability of hydropower.

On the demand side, previous studies often indicate an increase in electricity consumption under future climate change, such as in USA (Baxter and Calandri, 1992; Sailor and Pavlova, 2003; Mansur et al., 2008), the Southeast Mediterranean region (Cartalis et al., 2001) and Brazil (de Lucena et al., 2010). A net increase in demand is also indicated in Austria and German (Totschnig et al., 2017). In contrast, the total EU's energy demand is expected to decrease (Dowling, 2013). Similarly, a study for Norway (Seljom et al., 2011) also suggests a net decrease in energy demand.

Several studies integrate climate change multiple impacts on energy demand and various types of energy supply into the simulation of long-term power system expansion, thereby allowing to trace their combined effects on the system. Lucena et al. (2010) incorporate climate change impacts on electricity demand, hydropower, and natural gas turbines into the long-term expansion of the Brazilian power sector using MAED-MESSAGE models. Seljom et al. (2011) employ MARKAL to include climate change impacts to hydro and wind power as well as energy demand into the analysis of future Norwegian energy system. Meanwhile, Dowling (2013) analyzes the long-term European energy system considering climate change impacts on energy demand and various types of power supply, including thermoelectric, wind, solar PV, and hydroelectric by utilizing POLES. A similar study for Europe was conducted by Mima and Criqui (2015) with a smaller scope, covering only energy demand, thermal power plants, and hydropower. Totschnig et al. (2017) employ HiREPS to integrate impacts of climate change and fuel price shocks on energy demand and various types of energy supply into simulations of the future Austrian and German power sectors. Finally, Li et al. (2014) incorporate effects of projected changes in temperature, precipitation, and extreme events on electricity demand and various power supply types into the power system expansion for several U.S. regions using a robust electric power Generation Expansion Planning (GEP) optimization model. All these studies agree that thermal power plants' reliability will decrease under climate change. Meanwhile, climate change impacts on solar PV and wind are estimated to be minor (Seljom et al., 2011; Dowling, 2013). Results for Norway reveal lower system costs due to the net decrease in demand. Furthermore, the country benefits from an increase in hydropower production. Meanwhile, Brazil suffers from reduced hydropower reliability, needing extra installed capacity, consequently requiring extra investment costs.

Nevertheless, to the best our knowledge, research explicitly linking the impacts of climate change with the sector's climate mitigation goals is still lacking. Hence, the interferences of climate change impacts on the power sector's mitigation efforts for achieving national long-term climate mitigation goals, remain unexplored. An integrated assessment of climate change mitigation and adaptation for the power sector is especially vital for developing countries, which already face adverse climate change impacts and electrification needs on top of climate change mitigation goals. Therefore, this chapter addresses this important gap by pursuing a comprehensive assessment of the nexus between electrification, climate change mitigation, and climate change adaptation in developing countries, taking Indonesia as an example.

5.3. Methodology and data

This chapter simulates the future development of Indonesia's power sector, considering both climate change mitigation (low-carbon electrification) and adaptation, focusing on the country's primary power system. Fig. 5.1 depicts the conceptual framework of this chapter.

To account for climate change mitigation, this chapter sets a long-term scenario for the Java-Bali power system expansion taking into account the country's low-carbon development policy (Fig. 5.1, left flow). Subsequently, LEAP is used to analyze the low-carbon pathway. For the adaptation[11] part, I take a 3-step approach (Fig. 5.1, right flow). Firstly, I collect data on the current impacts of severe weather events and gradual changes in climate variables on different power plants, transmission and distribution networks by conducting semi-structured interviews and focus group discussions between February-March 2018 (as reported in Chapter 4). Secondly, I perform a literature review on climate change scenarios to identify the likely trends in temperature, precipitation, and sea surface

[11]Here, adaptation id defined as the variations in the power system configuration (e.g., installed, capacity, technology composition) due to the climate change-induced reduction in power supply reliability and changes in the electricity demand

temperature for the Indonesian archipelago. Finally, I identify the variables and functions in the LEAP model architecture to parameterize the projected impacts of climate change on the Java–Bali power system.

This chapter considers the impacts of climate change on both demand and supply sides. On the demand side, this chapter estimates how changing temperatures might affect electricity needs in Java–Bali. Meanwhile, on the supply side, it quantifies climate change impacts on power generation, focusing on four power plant types: CFPP, NGPP, HEPP, and solar photovoltaic (solar PV). The first three are chosen because they constitute most of Indonesia's power generation capacity, i.e., 50%, 28%, and 9%, respectively (KESDM, 2018c). This chapter also includes solar PV because, as indicated in Chapter 2, it plays a significant role in Indonesia's transition to the low carbon energy system.

This chapter focuses on analyzing the impacts of gradual changes in climate variables, including surface air temperature, precipitation, and sea surface temperature on the power system. Although extreme weather events often cause power failure, especially in distribution networks (see Chapter 4), they are not included in this chapter. This will be an essential topic for future research. WEAP is employed to analyze the impacts of changes in precipitation and temperature on the water availability for hydroelectric power plants. Meanwhile, this chapter relies on findings from Chapter 4 and on the current literature to parameterize expected climate change impacts on thermal power plants (TPPs) and solar PV.

Finally, I simulate the Java–Bali power system expansion taking into account the national low-carbon policy targets and climate change impacts on the power system. These simulations quantify electricity mix and corresponding costs of a climate-resilient power system that assures a nexus of electrification, climate change mitigation, and adaptation goals.

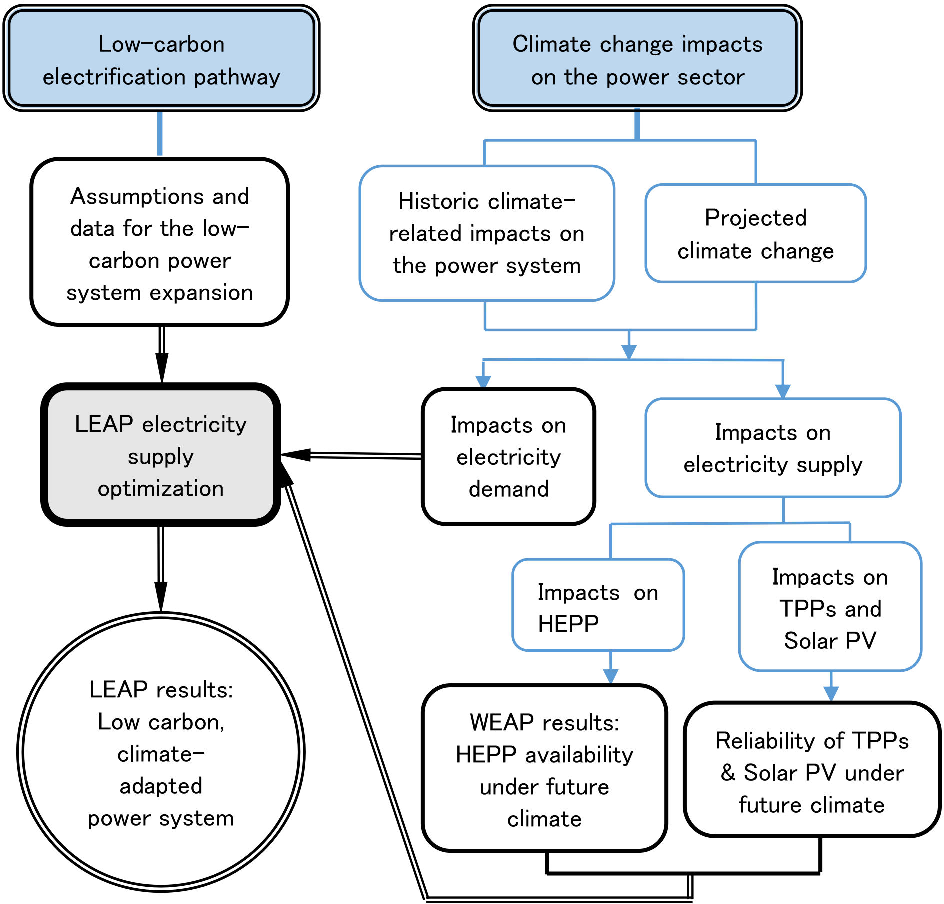


Fig. 5.1: The conceptual framework for integrating climate change mitigation and adaptation using WEAP-LEAP models

5.3.1. Scenario development

5.3.1.1. Climate change scenarios

The climate change projection in this chapter is based on the Representative Concentration Pathway (RCP) 4.5 and RCP8.5 scenarios adopted in AR5. RCP4.5 is one of the medium stabilization scenarios, assuming a stable radiation intensity at approximately 4.5 W/m^2 or equivalent to 650 ppm CO_2e after 2100. RCP8.5 is the one very high baseline emission scenario, which assumes a constant rise pathway leading to 8.5 W/m^2 of the radiation intensity (more than 1,370 ppm CO_2e) in 2100 (Zhang et al., 2017). Accordingly, this chapter uses climate change projections for Indonesia under these scenarios. The projection of temperature and precipitation (Table 5A.1 of Appendix 5.A) are based on the ensemble values of 35 CIMP models available at the World Bank Climate Knowledge Portal's website (The World Bank Group, 2019), which were derived from Harris et al. (2014). These data are available for two periods within the study's time horizon: 2020–2039 and 2040–2059. Meanwhile, the projected sea surface temperature (SST) data comes from a global climate model's output of the Institut Pierre Simon Laplace, which was retrieved from the International Pacific Research Center's website[12] (International Pacific Research Center, 2018). Based on these data, this chapter quantifies the effects of the changes in these climate variables on the electricity demand and on the key technical characteristics of various power plants.

5.3.1.2. Power system expansion scenarios

I develop three scenarios of the Java-Bali power system's expansion for the period of 2018–2050:

1. *Reference scenario* (REF): the power system's expansion scenario without climate change considerations. Hence, the objective of this scenario is to satisfy solely the growing future demand for electricity in the Java-Bali islands at the lowest cost.
2. *Climate change mitigation scenario* (CCM): the power system's expansion assumes a shift to a low-carbon pathway following the NRE targets stipulated in NEP, which is to increase the share of renewables in the national energy mix up to 23% by 2025 and 31% by 2050. In addition to these mitigation targets, this scenario accounts for

[12]The Asia-Pacific Data Research Center is a part of the International Pacific Research Center at the University of Hawai'i at Mānoa, funded in part by the National Oceanic and Atmospheric Administration (NOAA).

electrification but neglects the sector's adaptation to the changing climate.

3. *Climate change mitigation and adaptation scenarios* (CCMA): the power system's expansion assumes a shift to a low-carbon pathway and integrates the effects of projected climate change on the electricity supply and demand. Following the climate change scenarios discussed in Section 5.3.1.1, this chapter differentiates between two CCMA scenarios:
    a. CCMA RCP4.5: climate change impacts on power plants are quantified based on the IPCC RCP4.5 scenario
    b. CCMA RCP8.5: climate change impacts on power plants are quantified based on the IPCC RCP8.5 scenario

Chapter 2 and Chapter 3 have explained the setup of the Java-Bali LEAP model in detail. In addition to the methodological advances with the CCMA scenario, this chapter updates the previous ones by including the most recent historical data of energy demand and supply. Accordingly, the LEAP base year is updated from 2015 to 2017. Furthermore, this chapter updates the electricity demand projection by the most recent RUPTL 2018-2027 (PLN, 2018), which indicates a lower growth in electricity demand compared to the previous projection. Likewise, the capital cost of electric power technologies is now assumed to decrease every five years following the percentage of technology cost reduction in the World Energy Outlook (OECD/IEA, 2017).

5.3.2. Integrating adverse climate change impacts into LEAP

5.3.2.1. Demand-side

<u>Projecting impact of higher temperatures on the electricity demand</u>

By relying on the relationship between air temperature and electricity demand analyzed in Chapter 4 (Fig. 4.3, Chapter 4), I carry out a first-order estimate of the effects of projected higher temperatures on the annual peak demand.

Results show that the annual demand for electricity increases by 1.2% and 1.4% by 2020s under the CCMA RCP4.5 and CCMA RCP8.5 scenarios, respectively, relative to REF. Furthermore, by the 2040s the electricity demand increases by 2% and 2.8%, respectively.

5.3.2.2. Supply-side

As a bottom-up energy model, LEAP allows setting detailed characteristics of energy technologies through its input data. Hence, it is possible to alter the technical features of a power plant, integrating the effects of the changing climate. This chapter quantifies these effects based on the results of Chapter 4 and transforms them into changes in the technical characteristics of power plants. The altered technical features include the capacity factor and the efficiency of power plants, which are expected to influence the technology mix and installed capacity, as well as reflect the costs of the power system adapting to the changing climate.

Projecting impacts of temperature and precipitation changes to HEPPs

This chapter employs WEAP to simulate future hydrology in the Citarum river basin (Fig. 5B.1 of Appendix 5.B) based on projected changes in air temperatures and precipitations. The Citarum river provides water for the two largest HEPPs in Indonesia, i.e., Saguling and Cirata; each has the installed capacity of 1,008 MW and 797 MW, respectively. As discussed in Chapter 1, WEAP has a built-in link with LEAP, where the hydropower availability modeled by WEAP becomes an input for LEAP. Hence, the use of both software tools enables dynamic analyses of climate change implications on hydropower production (Spalding-fecher, 2018). Table 5B.1 of Appendix 5.B lists WEAP input data for the HEPPs simulations.

Results show that under the CCMA RCP4.5 scenario, the average annual capacity factor of both Saguling and Cirata HEPPs varies across years when compared to REF (Fig. 5B.2 of Appendix 5.B). From 2022 to 2039, both Saguling and Cirata produce slightly less electricity (<1%) compared to REF. In contrast, their electricity production overshoots that of REF from 2040 onward. However, the aggregate HEPP production over the study period is higher than that in REF. Meanwhile, no significant difference found in the annual average capacity factor across the years between REF and the RCP8.5 scenario. Nonetheless, the aggregate HEPP production in RCP8.5 is slightly lower compared to REF. These results are extrapolated to the rest of HEPPs when simulating the Java-Bali power system expansion using the LEAP-WEAP combination.

Sea surface temperature and efficiency of coal-fired power plants

A cooling water system is an essential part of coal-fired power plants. CFPPs in the Java-Bali power system rely on seawater for their cooling systems, thereby will likely be impacted by higher seawater temperatures expected in a climate-changed world. The CFPPs employ once-through cooling systems, which take water from the sea and circulate it through pipes in a condenser to absorb heat from the steam. The warmer water is then discharged back to the sea. A higher cooling water temperature results in a higher condenser pressure, which reduces the energy efficiency of a condenser (Haldkar et al., 2013). In Chapter 4, I drew the correlation between seawater temperature and condenser pressure of the Paiton PJB CFPP, which is a typical CFPP using a once-through cooling system (Fig. 4.4, Chapter 4). Here, this relationship is combined with the data of the primary energy consumption of the power plant. According to the power plant's performance report, every 1°C increase in cooling water temperature above 25°C, the power plant efficiency drops by 0.32%.

This chapter adopts this relationship to estimate the alteration of CFPP's efficiency following the changes in the sea surface temperature anticipated with climate change. Results show that the reductions of the efficiency of the Java-Bali CFPPs range from 0.1% to 0.4% under the RCP4.5 scenario and from 0.03% to 0.3% in the RCP8.5 scenario. These drops of efficiency are expected to increase fuel consumption, leading to a rise in fuel costs and CO_2 emissions.

Precipitation and capacity factors of coal-fired power plants

The fieldwork reveals that heavy precipitation dampens coals in CFPPs' open storage areas, thereby reducing the CFPPs' burning efficiency. This instance often occurs during the wet season when rainfall is intense and frequent. Suralaya CFPP, the largest CFPP in Indonesia, provides the operation disruption data from 2011 to 2017, which includes past disruptions due to wet coals. Based on this data, the average annual reduction of the CFPP's capacity factor is calculated, following the decrease in its energy generation attributable to wet coals.

Furthermore, this chapter combines the historical data of the CFPP disruptions and local precipitation, with projected precipitation under climate change scenarios to estimate reductions in the CFPP's capacity factor under future climate. Results indicate that the CFPP's capacity factor will reduce by 0.29% and 0.30%, respectively, by 2020 and 2040. These estimates are adopted in LEAP simulations for the rest of Java-Bali CFPPs.

Ambient air temperature and power output of natural gas power plants

There exist two types of technologies in NGPPs of the Java-Bali power system: NGOC, which produces electricity solely from a gas combustion turbine, and NGCC, which produces electricity from the gas combustion turbine and generates extra electricity by routing the waste heat from the gas turbine to the nearby steam turbine. High ambient air temperatures affect gas turbines of NGPPs. The operation of the gas turbines requires ambient air for the compressor intake and routed into the burning chamber. The higher the ambient air temperature, the lower the air density and, hence, the burning efficiency, which in turn reduces power outputs of the gas turbines (Henry and Pratson, 2016). According to the field data from the Muara Karang NGOC, every 1°C increase in ambient air temperature above 16°C, the power output of the NGOC drops by 0.6%. Accordingly, the power output of the Muara Karang NGOC correlates with air ambient temperature following Eq. 5.1. This data is comparable with findings reported in the literature, which indicate that with each one-degree temperature increase above 30°C, the power output of gas turbines drops by 0.50%–1.02% (Drbal et al., 1996; Kehlhofer et al., 2009; Asian Development Bank, 2012).

Furthermore, the literature indicates that the overall net reduction of the power output of an NGCC is within the range of 0.3% – 0.6%. Here, I assume that every 1°C increase in ambient air temperature, the power outputs of NGCCs drop by 0.45%, which is the middle value of the range. Accordingly, the power output of NGCCs correlates with air ambient temperature following Eq. 5.2.

Thus, this chapter estimates the monthly energy output of NGOC and NGCC under climate change scenarios based on projections of average monthly temperature, using Eq. 5.1 and Eq. 5.2, respectively. Accordingly, the annual capacity factor under climate change scenarios is calculated using Eq. 5.3. Results show that reductions in the capacity factor of the Java-Bali NGPPs in 2040 range from 0.8% to 4.3%.

$$P(T) = P * (-0.006T + 1.0933) \quad \text{Eq. 5.1}$$

$$P(T) = P * (-0.0043T + 1.0662) \quad \text{Eq. 5.2}$$

$$CF_{Tm} = \frac{E_{Tm}}{Plant\ capacity\ (MW) * 8760\ hours} \quad \text{Eq. 5.3}$$

where E_{Tm} is the annual energy output in MWh, Tm is the average monthly temperature, $P(T)$ is the power output at temperature T in MW, and CF_{Tm} is the capacity factor.

<u>Air temperatures and efficiency of Solar PV</u>

A rise in air temperature may negatively impact the performance of solar PVs. It manifests as a decrease in the solar PV efficiency determined by the so-called temperature coefficient, which is a correction factor of efficiency as a function of temperature (Simioni and Schaeffer, 2019). This chapter adopts the estimate by Pašičko et al. (2012), where every 1°C increase in air temperature decreases PV efficiency by 0.5% relative to the referent value at 25°C. This value is consistent with the average temperature coefficient specified in Dubey et al. (2013). Based on this assumption, this chapter estimates the reduction in the efficiency of the Java-Bali solar PV following the climate-driven rise in temperature[13]. Results indicate that the reduced efficiency under future air temperature leads to a reduction in the solar PV capacity factor by 0.5% to 0.6% during the 2020s and by 0.8% to 1.1% during the 2040s.

5.4. Climate change mitigation-adaptation synergies: LEAP Results

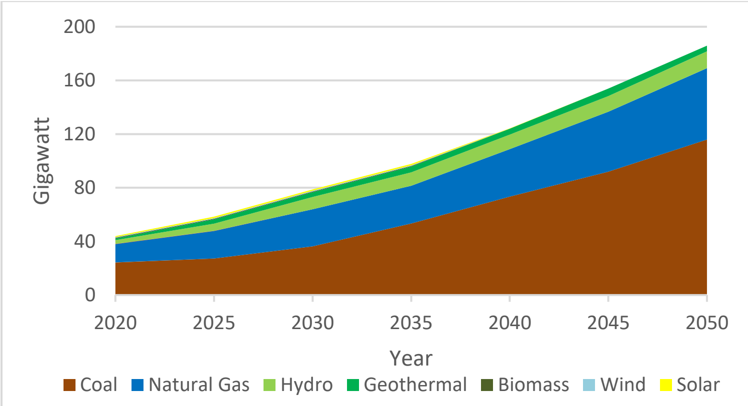
The following sections discuss the output of the climate change mitigation-adaptation integrated framework using WEAP and LEAP models applied to the case of the Java-Bali power system. First, the capacity added and electricity mix for each scenario are presented, followed by discussions on their associated costs and CO_2 emissions.

5.4.1. Installed capacity and electricity mix

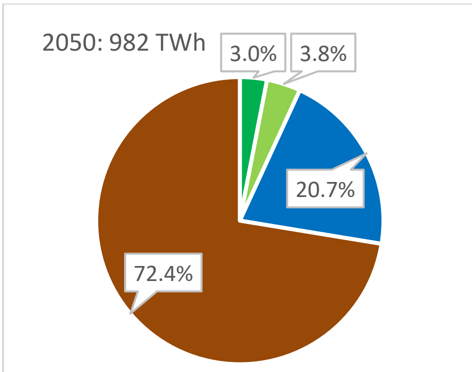
5.4.1.1. Reference scenario

In the reference scenario, which assumes the least-cost electrification without considering climate change mitigation and adaptation, the capacity of fossil fuel technologies increases rapidly. The coal and natural gas capacity reach 115 GW and 53 GW by 2050, respectively, hence increase sixfold and fivefold compared to 2017. As a result, the capacity mix over the study period locks into the fossil fuels' regime (Fig 5.2a). Therefore, in 2050, coal maintains its domination (Fig. 5.2b), comprising 72.4% of the Java-Bali electricity mix, followed by natural gas (20.7%), hydro (3.8%), and geothermal (3%).

[13]This study assumes that other parameters (e.g., wind speed, solar radiation) remain unchanged



(a)



(b)

Fig. 5.2: Capacity mix over the study period (a) and electricity mix in 2050 (b) in the reference scenario

5.4.1.2. Climate change mitigation scenario

Results show that the implementation of NEP's NRE policy (climate change mitigation targets assumed in the CCM scenario) dramatically alters the Java-Bali capacity mix. In 2050, the coal capacity in CCM reduces by 41% compared to REF. The reduction in the coal capacity is compensated by the increased capacity of natural gas (23%), hydro (7%), and geothermal (27%) as well as by the penetration of solar (117.7 GW), biomass (7.4 GW), and wind (1.6 GW). With this capacity mix, all of the hydro, geothermal, and biomass potentials in Java-Bali islands (Table 5B.1 of Appendix 5.B) are utilized, leaving wind and solar as the only renewable energy source still potentially available.

Accordingly, the Java–Bali electricity mix mimics the change in its capacity mix. While fossil fuels serve most of the demand for electricity in the base year, they gradually reduce their share in the Java–Bali electricity mix. Complying with the NRE target, by 2025, renewables compose 23% of the electricity mix, shared between geothermal (9.6%), hydro (5.6%), biomass (6.5%), wind (1%), and solar (0.3%) (Fig. 5.3).

Furthermore, by 2050, the renewable share increases up to 31% as targeted by NEP. Interestingly, the electricity production from solar encompasses 17.4% of the total electricity mix, the highest among other renewable owing to the relatively faster reduction in its investment costs. Meanwhile, although nuclear is available as an option for meeting the NRE targets, it is not competitive against solar and other renewables due to its low technology-learning rate.

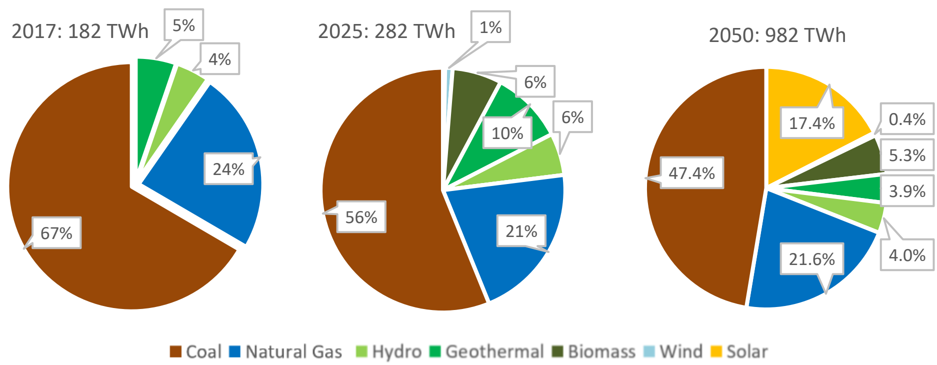


Fig. 5.3: The Java–Bali electricity mix in 2017, 2025, and 2050; climate change mitigation scenario (CCM)

5.4.1.3. Climate change mitigation and adaptation scenarios

When impacts of global climate change are integrated on top of the climate change mitigation and electrification assumptions, the results depict the optimal choice of shifting the Java–Bali power system to a low-carbon pathway while also responding to the effect of new climate conditions. The results show that extra capacities are required to serve the climate-induced electricity demand surge and to cope with the decreased power-generating capacity (Fig. 5.4). Under CCMA RCP4.5, the extra capacity of solar PV, coal, wind, and biomass are 7.5%, 5.4%, 19.9%, and 0.7%, respectively higher from that in CCM. In contrast, the natural gas capacity reduces by 2.2% compared to CCM. Naturally, the capacity of solar PV, coal, wind, and biomass increase to balance the growth in demand and to compensate for the declined power-generating capacities.

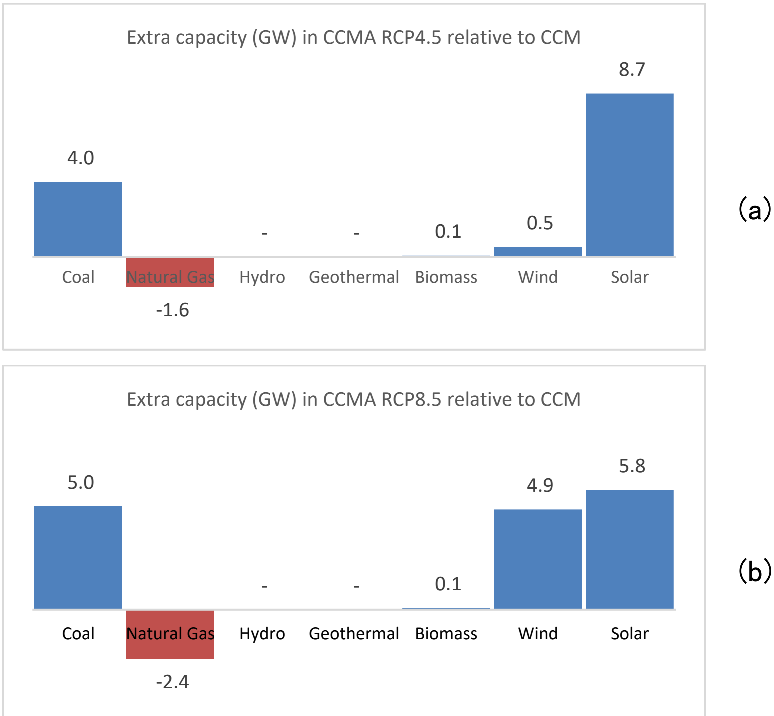
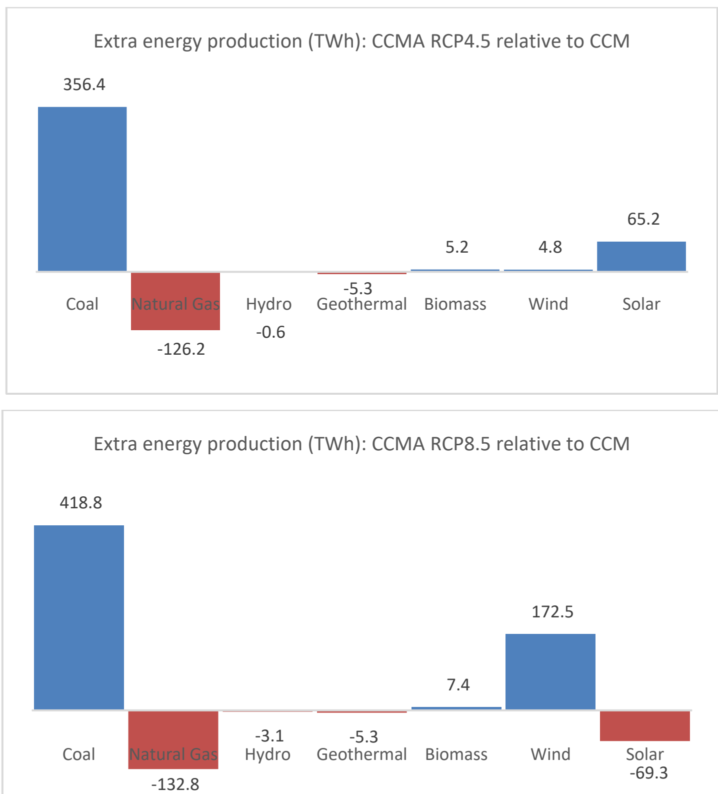


Fig. 5.4: Extra capacity in CCMA RCP4.5 (a) and CCMA RCP8.5 (b). CCM is taken as a benchmark

Under CCMA RCP8.5, the extra installed capacity is even higher, which indicates that the higher temperature scenario intensifies impacts on the electricity demand and power supply (e.g., coal, natural gas, solar PV). The extra capacity is now shared almost evenly between solar, coal, and wind (Fig. 5.4b). The increased penetration of wind power indicates the trade-off between climate change mitigation and adaptation. Firstly, wind resource potential is still available to facilitate the power system meeting the NRE targets while the addition of the coal capacity is constrained by NRE targets. Secondly, the simulation excludes the impacts of climate change on wind power. Thus, under the higher temperature scenario (CCMA RCP8.5), wind power replaces a portion of solar PV's extra capacity, making the extra capacity of solar PV lower than that in CCMA RCP4.5. However, the role of solar PV is still significant in anticipating the climate-induced surge demand, adding extra capacity above CCM by 5%.

Furthermore, the extra installed capacity to anticipate climate change adds 299 TWh and 388 TWh of electrical energy, respectively, in CCMA RCP4.5 and CCMA RCP8.5, over the period of 2020–2050. In CCMA RCP4.5, the additional electrical energy mainly comes from coal and solar PV (Fig. 5.5a). Meanwhile, although solar adds extra capacity in CCMA RCP8.5 (Fig. 5.4b), its electricity generation is 6% lower than that in CCM likely due to a reduction in its efficiency, which is compensated by a significant increase in wind power production (Fig. 5.5b).



(a)

(b)

Fig. 5.5: Extra electricity production in CCMA RCP4.5 (a) and CCMA RCP8.5 (b). CCM is taken as a benchmark

5.4.2. O_2 emissions and total costs

5.4.2.1. CO2 emissions

Indonesia's NDC outlines the country's target of reducing 29% of its emission from business as usual (BAU) by 2030, where the energy sector is targeted to contribute 11% of the national CO_2 reduction target or 19% reduction from its emission baseline. The simulation results reveal that under the reference scenario, the Java-Bali power system emits 215 million tons of CO_2 in 2030 (Fig. 5.6). This value is lower than that was calculated in Chapter 3, mainly because of the lower electricity demand growth assumed in the present chapter – following the latest RUPTL – compared to Chapter 3. Meanwhile, under the CCM scenario, the CO_2 emissions decrease to 188 million tons, which is 13% lower than that in REF. Therefore, under the updated assumption, additional efforts beyond implementing NEP's NRE targets are required to achieve the NDC target by 2030. By 2050, however, the CO_2 emissions drop further, being 34% lower than that in REF. Therefore, when the NRE target in 2050 is fulfilled, Indonesia can reduce its emission further, moving beyond its current NDC.

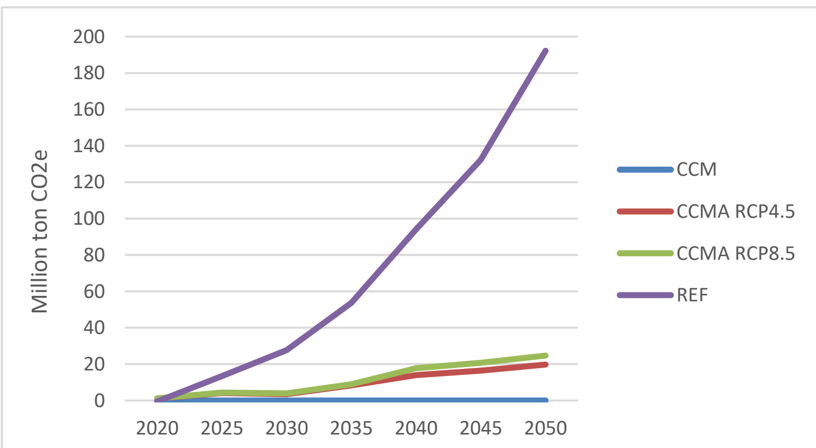


Fig. 5.6: CO_2 emissions under reference, mitigation, and adaption scenarios. CCM is taken as a benchmark

The CO_2 emissions increase in both CCMA scenarios, i.e., 20 and 25 million ton CO_2, respectively, in RCP4.5 and RCP8.5 (Fig. 5.6) compared to CCM. The additional CO_2 emissions are attributed to the increased electricity production from coal to compensate for the climate-induced surged electricity demand. Moreover, CFPPs efficiencies drop under future climate, needing additional fuel coal consumption per unit energy produced. However, even with this increase, the CO_2 emissions still decrease by 30% compared to REF in 2050.

5.4.2.2. Total costs

Total costs are calculated based on the net present value of the total costs over the entire study period, which includes capital costs, operation, and maintenance costs, and fuel costs. Under REF, the total costs of electricity production over the simulation period 2018–2050 reach 70.4 billion USD, which is equal to 0.1% of the cumulative national GDP during the study period[14]. This is lower than estimated in previous work (Chapter 3), partly owing to the lower electricity demand growth assumption in the present research following the update in the latest RUPTL (PLN, 2018) and due to the assumption of technology cost reduction, which is now included in all scenarios.

Meanwhile, under the CCM scenario, the total costs of expanding the Java-Bali power system over the period of 2018–2050 reach 75.1 billion USD. Hence, shifting from the current regime to the low-carbon pathway adds 4.7 billion USD extra or 6.8% higher costs compared to the no mitigation-adaptation scenario (REF) (Fig. 5.7). Furthermore, when climate change impacts are considered, the costs grow by 10.7% and 11.4% in CCMA RCP4.5 and CCMA RCP8.5, respectively, relative to REF. This implies that shifting to a low-carbon power system while coping with climate change impacts increase the sector costs relative to the no mitigation-adaptation scenario. Thus, the climate change mitigation-adaptation costs for the Java-Bali power system are 2.7 and 3.2 billion

[14]Assuming annual GDP growth of 4.5%

USD, respectively higher than the costs when only climate change mitigation is considered (compare CCMA RCP4.5 and CCMA RCP8.5 with CCM in Fig. 5.7). These costs are high: they constitute more than half of the budget allocated by the Indonesian Government for climate change mitigation and adaptation for all sectors in 2017. These additional costs are due to the extra installed capacity and energy production of coal, solar PV, and wind power required to cope with the adverse impacts of future climate.

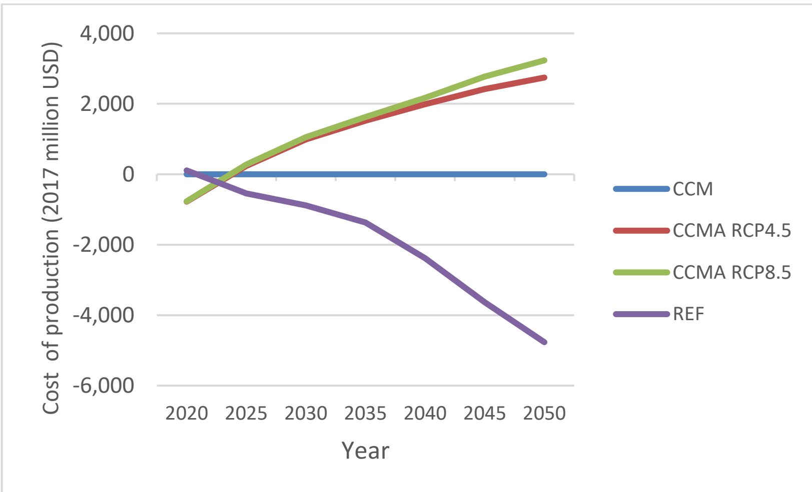


Fig. 5.7: Total production costs under reference, mitigation, and adaption scenarios. CCM is taken as a benchmark.

5.5. Discussion

The integration of climate change mitigation and adaptation objectives into the simulations of the Java-Bali power system expansion reveals the following findings. First, the Java-Bali technology composition is significantly altered, driven by the constraints set in LEAP, i.e., the minimum amount of renewable energy share and the adverse climate change impacts. Second, the Java-Bali installed capacity increases to balance the climate-induced increase in electricity demand and to compensate for a loss of reliability of the Java-Bali power generation due to new climate conditions. Finally, while CO_2 emissions drop due to the mitigation efforts, the total costs of the electricity production increase by 11.4% in 2050 attributed to the mitigation and adaptation measures.

The NEP's NRE targets force the power system to shift to a low-carbon pathway, resulting in a 34% CO_2 emission reductions by 2050. The main driver of this transition is solar PV owing to its vast remaining exploitable potential, whereas the exploitable potential of other renewables such as hydro and geothermal is limited. Likewise, solar PV also plays a significant role in compensating for the reduction in capacity and energy generation under adverse climate change impacts, especially under CCMA RCP4.5. However, under the higher temperature changed scenario (CCMA RCP8.5), solar PV reduces its reliability, which is compensated by wind power. Meanwhile, coal plays a significant role in satisfying the climate-induced increase in electricity demand and compensating for the declined power-generating capacity in both CCMA scenarios, resulting in an increase of CO_2 emissions compared to CCM. These findings clearly show the interplay between climate change mitigation-adaptation objectives and suggest that climate change impacts might hinder climate change mitigation efforts of the power system, which agrees with the hypothesis in the literature (Fisher-Vanden et al., 2013; Turner et al., 2017; Cronin et al., 2018).

Given that climate change impacts are unavoidable due to the past emitted CO_2 and the delayed mitigation actions, these findings suggest several courses of action for policymakers. First, a key policy priority should be to recognize the power sector's vulnerability to climate change, prepare for its adaptation action plans, and further integrate the plans into the national adaptation strategies. Secondly, there is a defined need for ensuring a sufficient budget allocation for the power sector's adaptation to climate change. Since the power sector adaptation to climate change hinders the CO_2 mitigation efforts, a nexus between mitigation and adaptation energy policy should be exploited in national budget allocation. Finally, more considerable efforts are needed for conducting detailed investigations of climate change impacts on individual power plants, including a full analysis of the cost and benefit of their adaptation. The latter may include local investments in preventing reductions in capacity factor and efficiency at individual vulnerable power plants.

5.6. Conclusions

The main goal of this chapter is to integrate both climate change mitigation and adaptation objectives into the long-term capacity expansion of a power system. This chapter takes Indonesia as an example of a developing country struggling to meet its electrification needs, focusing further on its primary power system, i.e., Java-Bali. Four scenarios for the Java-Bali power system expansion from 2018 through to 2050 are analyzed, including a reference scenario, a climate change mitigation scenario, and two scenarios that integrate climate change mitigation and adaptation. For climate change mitigation, this chapter considers the renewable energy target of the Indonesian government that aims to increase the share of new and renewable energy by 23% in 2025 and 31% in 2050.

Meanwhile, this chapter quantifies climate change impacts on power supply and demand by employing various methods. The WEAP model is used when quantifying climate change impact on hydropower availability, and combine empirical data from the fieldwork with findings from the literature when assessing climate change impacts on thermal power plants and on the electricity demand. The estimated impacts include the changes in HEPP's capacity factor, a reduction in CFPP's efficiency and capacity factor, a reduction in NGPP's capacity factor, a reduction in solar PV capacity factor, and an increase in electricity demand. Furthermore, this study integrates these quantified impacts into the Java-Bali power system expansion using LEAP. The simulation results are discussed in terms of installed capacity, electricity mix, costs, and CO_2 emissions.

This chapter provides an insight into economically optimal options for the electricity generation in the Java-Bali power system under a set of climate change mitigation-adaptation regimes. It includes impacts on the demand as well as on the supply sides. Although this chapter does not cover climate change impacts for all types of power plants, results indicate significant deviations from the reference scenario in terms of installed capacity, electricity generation, and the total costs of electricity production, attributable to climate change mitigation and adaptation. Furthermore, even though this chapter excludes the impacts of extreme weather events, the costs of power system adaptation to gradual changes in climate variables such as temperature and precipitation are comparable with the costs of climate change mitigation.

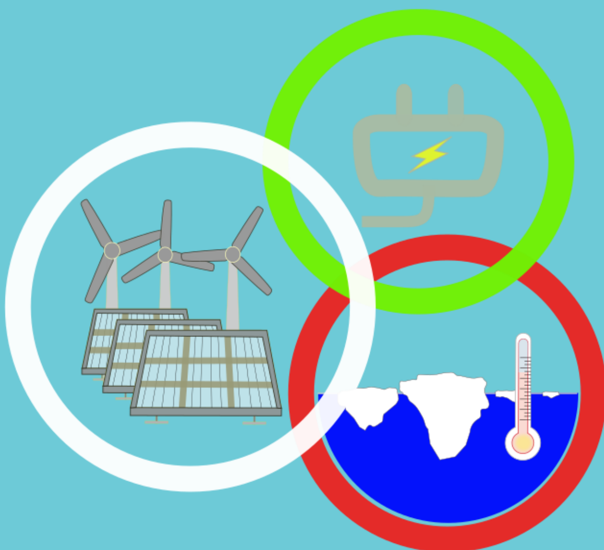
The methodological approach of this chapter could be replicated in other cases that aim at analyzing the interplay between climate change mitigation and adaptation in the power sector. This chapter, however, has several limitations, mainly regarding the assessment of climate change impacts on power generation. Firstly, the projection of climate change impacts on the Indonesian power sector is preliminary, driven by the estimates found in the literature rather than a case-specific downscaled climate change scenario. Yet, this secondary data provides the basis for an initial evaluation regarding climate change impacts on the power sector. Furthermore, this chapter generalizes the effects of climate change on CFPPs and HEPPs based on the fieldwork data from several power plants. Future work may focus on collecting detailed data on individual power plants to assess site-specific costs of climate change and possible adaptation solutions.

Secondly, the modeling approach in this chapter does not include impacts of extreme weather events, whereas they may intensify under future climate change and lead to physical infrastructure damage, energy losses, and indirect effects such as business interruption. This would be a fruitful area for further work. Thirdly, due to data limitations and the scope of LEAP, climate change impacts on transmission and distribution are excluded from this assessment. Further research may explore the quantification of climate change impact on the entire segments of the power sector: generation, transmission, and distribution. Finally, the analysis in this chapter relies on global climate change projection for which there is a great deal of uncertainty. Therefore, the modeling of climate change impacts on electricity supply and demand inherits the uncertainty of the chosen climate change scenarios.

Despite its limitations, this chapter provides a methodological framework for an integrated analysis of climate change mitigation and adaptation in the power sector, which allows an assessment of the nexus between climate change mitigation and adaptation that crucial for developing optimal mitigation and adaptation strategy. This framework can be extended to account for other climate change impacts such as extreme weather events, impacts of gradual changes in climate variables on transmission and distribution networks, and impacts on other types of electric power technology such as wind power, geothermal, nuclear, and storage technologies.

6

Synthesis of the Dissertation



6.1. Introduction

The global power sector faces a triple challenge: to satisfy fast-rising electricity demands, to meet the sector's CO_2 reduction targets, and to cope with the adverse impacts of climate change. These challenges require the power sector's transformation to low-carbon and climate-resilient systems. Moreover, financial institutions and credit rating agencies have included climate change risks into their assessment criteria, calling for the enhancement of the electric industry's resilience to climate change (International Finance Corporation, 2012; Connell et al., 2018; Mufson, 2019). Accordingly, international standards are emerging to assist electric utilities in examining climate change impacts and developing adaptation strategies. For example, the World Bank produced a guideline for climate-resilient hydropower (World Bank, 2017), while the International Organization for Standardization recently established ISO 14090: Adaptation to climate change — principles, requirements, and guidelines (Naden, 2019)

A practical barrier to the low-carbon and climate-resilient transformation is the fact that expanding the power system, even without climate change consideration, involves enormous investment costs (Bhattacharyya, 2011; Nicolas et al., 2019). Furthermore, while technological change is required to facilitate this transformation (Nakicenovic et al., 2000; Berglund and Söderholm, 2006; IPCC, 2007; Wilson and Grubler, 2011), it needs to be supported by institutions and economic incentives (Pachauri et al., 2014).

Meanwhile, the scientific challenge concerning this societal problem lies in developing a method for an integrated analysis of electrification, climate change mitigation, and climate change adaptation in the power sector. Likewise, modeling technological change to support low-carbon transition remains a challenge for energy modelers (Grübler et al., 1999; Frei et al., 2003; Berglund and Söderholm, 2006).

Thus, the **goal** of this doctoral research was to contribute to addressing the above scientific challenges by assessing the triple nexus of electrification, climate change mitigation, and climate change adaptation in the power sector. I have addressed four core **research questions** based on the Java–Bali power system in Indonesia by employing energy and water sectors simulation modeling using LEAP and WEAP, respectively, and by conducting extensive fieldwork. The fieldwork involved in-depth, semi-structured interviews and focus group discussions with representatives of electric utilities within the Java-Bali power system. Furthermore, I have conducted this doctoral research project in four stages, as discussed in greater detail in Chapter 2 through Chapter 5.

This chapter proceeds as follows: Section 6.2 summarizes the findings from each study, followed by the highlights of the innovative contributions of this dissertation (Section 6.3). Section 6.4 provides the policy implications of this doctoral research, while Section 6.5 reflects on the limitations of this dissertation and highlights the agenda for future research that aims at modeling power system expansion under the climate change regime.

6.2. Summary of the findings

RQ1: How could the power sector align electrification and the Paris Agreement goals?

To address RQ1, I conducted modeling simulations of the Java-Bali power system expansion, as reported in Chapter 2. To decide on a suitable model for performing simulations, a systematic screening of 48 energy models was performed. The screening resulted in the LEAP energy model being chosen for a number of reasons. Firstly, it can accommodate the detailed characteristics of electric power technologies. Secondly, its free access for developing countries increases the chances of reproducing the outcomes of this work and further development of methods beyond the scope of this dissertation. Lastly, its extensive use makes results comparable across countries.

Furthermore, I carried out a validation of the Indonesian LEAP model to test the accuracy of the LEAP analysis, comparing the LEAP simulation results for power system expansion from 2006 through to 2015 with the historical data. The results of this validation check conclude that LEAP predicted the expansion of the Java-Bali system from 2006 through to 2015 with an accuracy of 88.2%–100%. Relying on these results, I proceeded further by conducting simulations of the Java-Bali power system expansion from 2016 through 2030.

Three scenarios of the Java-Bali power system's responses to the Paris Agreement were simulated. These scenarios defined the power sector's CO_2 emission reduction target stipulated in Indonesia's NDC document as a constraint in the simulation. Hence, the future power generation needs to comply with the Paris Agreement while satisfying the national electrification objective.

The results revealed that in the context of the Java-Bali power system, electrification and Paris climate goals could be achieved solely through: (i) fuel switching from coal to natural gas or (ii) escalating renewable energy deployment. However, the economically optimal strategy was achieved due to the combination of an increase in natural gas power generation and in renewable capacities. This strategy led to a reduction of 65 million tons of CO_2, thereby meeting the NDC target at 18% and 12% lower costs than merely switching to natural gas or renewable energy, respectively.

The chapter concluded that the Paris Agreement could enforce the power system's transition from a fossil-fuel-based power generation to a low-carbon power system in Java-Bali, thereby lowering CO_2 emissions. However, this transition imposes higher total costs of the power system expansion compared to BAU, which should be considered in the national budget plan, as the Indonesian power sector is still highly subsidized.

RQ2: How could technological change affect the deployment of renewable energy?

To answer this research question, I incorporated the one-factor learning model into the LEAP cost function, which allowed a quantification of the endogenous technology cost reduction as a function of the accumulation of installed capacity of electric power technologies. With this modification, I have simulated the Java-Bali power system expansion from 2016 through 2050, taking into account the NRE targets.

Chapter 3 has elaborated the methodological framework to explore the cost-reducing effect of technological learning using LEAP and then, thereafter, discussed the findings. The learning rate of various electric power technologies, including fossil fuels and renewables, were taken into account in the simulations. Based on the WEO model assumption of capital costs reduction of electric power technologies (OECD/IEA, 2017), the chapter has parameterized four phases of technological learning in LEAP. The high speed of learning occurred during the initial phase, while its pace reduced gradually throughout the other three phases.

The study has shown that in the absence of technological learning, nuclear power is more cost-effective at meeting the NRE targets than solar PV and wind power. However, empirical data has proven that the costs of renewables decrease over time, while the costs of nuclear tend to increase (Rubin et al., 2015). Accordingly, when ETL was included in the LEAP simulations, renewables became competitive against nuclear. By 2050, solar PV will lead other renewables in assuring the achievement of NRE targets. As a result, the costs for achieving the NRE targets are 4% and 10% lower under the scenario of the medium and high pace of technological learning, respectively, compared to no technological learning scenarios. Furthermore, the achievement of NRE provides a co-benefit in terms of reducing emissions, assuring the fulfillment of the power sector's NDC target.

Overall, the chapter has concluded that endogenous technological learning accelerated the penetration of renewable energy in the Java-Bali power system and lowered the costs of achieving the NRE targets.

RQ3: How do severe weather and gradual changes in climate variables affect the power system? What are current adaptation practices?

Chapter 4 moved the focus of this dissertation to climate change adaptation. The research question of this chapter sought empirical evidence that could explain how and to what extent weather and climate have implications for the power sector. Data were collected through extensive fieldwork that was carried out in Indonesia between February and March of 2018. First, I designed questionnaires that were structured differently for each target group. After which, I conducted semi-structured interviews and focus group discussions involving the representatives of three electric utility companies. The latter was comprised of three head offices, ten power generation plants, a load control center (grid operator), two transmission offices, and two distribution offices, thus covered the entire chain of the electricity supply. The ten power plants are the major ones in the Java-Bali power system, accounting for 35% of the Java-Bali power generation capacity. Moreover, this chapter covered the entire Java-Bali T&D networks.

The results of this investigation revealed that severe weather and gradual changes in climate variables have implications for power generation, transmission, and the distribution of electricity. However, in terms of frequency of disruption event, distribution networks are affected most by severe weather events. Weather-related power cuts commonly occur due to failures in distribution networks. Meanwhile, the Java-Bali power generations recorded several forced outages due to extreme weather- and climate-related events, such as flood and jellyfish inflow into the cooling water system. For transmission networks, lightning strikes have become the leading cause of their failures.

Furthermore, Chapter 4 provided empirical evidence regarding the correlation between climate variables, such as air temperature, precipitation, and sea surface temperature, with the performances of the power plants. The evidence suggests that higher temperatures reduce the reliability of thermal power plants. Meanwhile, changes in precipitation patterns affect the operations of hydroelectric power plants, which in turn affect the operational pattern of the Java-Bali power system as a whole.

Another interesting finding was that weather- and climate-related disruptions caused financial losses for utility companies due to damaged equipment and energy-not-supplied. Subsequently, utilities have taken ex-post adaptation responses, which include managerial and technological interventions.

To summarize, these findings suggested that the Java-Bali power system is vulnerable to severe weather and gradual changes in climate variables. Therefore, future climate change is expected to increase the vulnerability of the power system, demanding that the system improve its resilience to climate change.

RQ4: How can one integrate climate change impacts into the power system expansion modeling? How might this affect electrification and climate change mitigation goals?

To answer this set of research questions, Chapter 5 brought together climate change mitigation and climate change adaptation within an integrated framework. Within this framework, the chapter has incorporated the anticipated climate change impacts into simulations of a low-carbon power system expansion from 2018 through 2050. Climate change impacts were quantified based on the empirical data from the fieldwork and then supplemented by the secondary data from the literature; for example, the global climate change projections downscaled for Indonesia. Furthermore, the WEAP software tool was used to simulate water availability for hydropower under the future climate. Meanwhile, quantifications of climate change impacts on coal and natural gas were based on empirical evidence from case study power plants and findings from the literature.

Thus, the research has shown that future climate change could have implications on electricity supply and demand. On the supply side, climate change reduced power-generating capacity while on the demand side, it increased the demand for electricity. Given these constraints as well as the requirement to achieve the NRE and CO_2 mitigation targets, the results of modeling simulations showed an alteration in technology composition compared to the electrification-only scenario.

Furthermore, extra capacities were required to compensate for the climate change-induced reduction in power-generating capacity and the increased demand in the above 2°C warmer world. Consequently, the total costs of power system expansion increased by 11.4% compared to no mitigation-adaptation scenario. Moreover, in the mitigation-adaptation scenario, CO_2 emissions in 2050 increased by 4% compared to the scenario that only considered the mitigation and electrification objectives.

The simulation results indicated that future climate changes would increase electricity demand and reduce the reliability of the power generation. These changes will cause an increase in CO_2 emissions and costs, indicating that climate change impacts on the power system might hinder the electrification and climate change mitigation goals if no climate change adaptation policy is developed for the sector.

6.3. Innovative contributions to science

This doctoral dissertation has provided insights into the interplay between electrification, climate change mitigation, and climate change impacts and adaptations. Accordingly, this dissertation makes several innovative scientific contributions to the literature on climate change mitigation-adaptation in the energy sector.

Electrification and Paris climate goals: Firstly, to the best of the author's knowledge, the study discussed in Chapter 2 was the first to assess the trade-offs between electrification and the Paris climate goals in the context of the Indonesian power sector using a technology-rich energy system model. Furthermore, the modeling simulations in this dissertation employed a high-quality dataset of the 67 power generation units in the Java-Bali power system, which included technical parameters crucial for LEAP input data. Hence, it enabled more accurate results for the Indonesian context than relying on the default values provided by the LEAP technology database. As reported in Chapter 2, the research results showed an agreement with other studies, assessing the implications of the Paris Agreement on the power sector (Grande-Acosta and Islas-Samperio, 2017; Baek et al., 2019; Kumar and Madlener, 2018) and in particular, those concerning an increase in the investment costs of the power system expansion, as well as in the penetration of renewable energy technologies.

Power system expansion and endogenous technological learning: Secondly, Chapter 3 demonstrated how ETL could influence renewable energy deployment in Java-Bali. Although LEAP has been used worldwide, to the best of the author's knowledge, this chapter was the first to integrate ETL into LEAP and applied it to simulations of a power system expansion. Therefore, this chapter adds to the understanding regarding the role of technological learning in driving the transition from a fossil-fuel-based power generation to a lower-carbon power system in the context of developing countries. Similar results regarding the role of ETL in energy transition are indicated in other studies, although with different contexts, such as Heuberger et al., which incorporate ETL into the ESO-XEL model for analyzing the UK's power system and Liu et al., which integrate ETL into TIMES for assessing the Tianjin power sector in China.

Empirical evidence of the impacts of weather and climate on the power sector. Thirdly, Chapter 4 has been one of the first attempts to thoroughly examine the historical impacts of weather and climate on the power sector. Hence, this chapter provides new data that adds to our understanding concerning weather and climate impacts on the sector, including direct damage costs suffered by utilities and their adaptation responses. Moreover, given the absence of vulnerability analysis of the Indonesian power sector to climate change, this chapter offers valuable insights into this important subject. Compared with few empirical studies on this subject (Audinet et al., 2014; Syariman and Heru, 2011), new findings have emerged, such as extreme weather events that caused jellyfish inflow and waste increase, which adversely affected the cooling water system of thermal power plants.

Integrated analysis of the power sector expansion under climate change mitigation and adaptation: Fourthly, Chapter 5 has explicitly linked the power system's climate change mitigation efforts with the interferences brought by climate change impacts to the power sector. Thus, this chapter contributes to filling the gap in the literature on the integrated analysis of climate change impact and adaptation in the energy sector, as highlighted by the IPCC AR5 (Clarke et al., 2014).

Assessment of climate change mitigation and adaptation of the energy sector on the global South: Finally, this dissertation takes Indonesia as a case study. In doing so, it adds to the scarce literature in developing countries regarding (i) the implications of the Paris Agreement on the power sector, and (ii) climate change impacts, adaptation, and vulnerability.

In addition, this dissertation creates *two methodological innovations* by advancing the LEAP model application:

Firstly, Chapter 3 extended the current practice of LEAP by incorporating the *ETL of electric power technologies into the LEAP cost function*. The modeling approach was reported in detail, thereby allowing its replication and application to other cases. Secondly, Chapter 5 advanced the LEAP model practice by incorporating *climate-driven changes in technological characteristics* (i.e., efficiency and capacity factor) of various power generation types. Thus, providing LEAP modeling framework for an integrated analysis of climate change mitigation and adaptation.

6.4. Policy implications

This doctoral research focused on one critical contemporary societal problem: electrification and climate change. The findings of this dissertation can be used to develop targeted interventions aimed at balancing electrification goals with climate change mitigation and adaptation goals. This is particularly important for the global South, where electrification is a precondition for the development and achievement of most social and economic UN SDGs. Accordingly, this dissertation suggests several courses of action for the Indonesian power sector:

Early deployment of renewable energy: Indonesia's NDC mitigation target is aligned with the national policy to increase the share of renewable energy in the national energy mix. The results in Chapter 3 have shown that the costs of renewables decrease following the increase in their installed capacity, with technological learning occurring at the highest speed during the initial phase of technology deployment. These findings suggest that the deployment of currently unexploited renewable energy should start as early as possible to gain the benefits of technological learning and to avoid further technological lock-ins of the newly installed infrastructure into fossil-fuel-based electricity production. Furthermore, this will help to avoid excessive investments in coal-fired power plants, which could result in stranded coal power plant assets in the future.

Enabling faster local learning: Developing countries like Indonesia generally receive technology transfers from industrialized countries, allowing Indonesia to take advantage of global technological learning that has already taken place. Additionally, local learning processes also play a significant role in reducing the costs of renewables. Therefore, the conditions that facilitate faster local learning should be made available. Such a condition includes a stable regulatory framework, an adequate skilled workforce, and the establishment of a sustainable business model (Huenteler et al., 2016). Infrastructure improvements that enable remote areas to become more accessible would also create a faster diffusion of renewable energy technologies. Most importantly, it is critical that there should be interactions between all involved parties, including users, suppliers, competitors, universities, and regulators for the learning and innovation process to occur (Lundvall, 2016).

Improvements in the grid capacity: Integration of vast renewable energy capacities presents new challenges to any power system operations and planning. Variable energy resources, such as wind and solar, have intermittent characteristics that will likely change the way electricity is dispatched and transmitted by the grid operator. Therefore, the acceleration of renewable energy deployment should go hand-in-hand with the improvement of grid capacity, which includes technical and human capital capacities. Furthermore, other disruptive technologies, such as the internet of energy, energy storage, and electric vehicles, require the global utility sector to transform into a smarter grid.

Moving toward a low-carbon and climate-resilient power sector: Chapter 4 has shown that severe weather and changes in climate variables have caused widespread power outages, resulting in tremendous financial losses for utilities and have affected the economy as a whole. Given the vital role of the sector in meeting the electrification and climate change mitigation goals, it is crucial for the country to improve the sector's resilience to climate change.

The first step toward a low-carbon and climate-resilient power sector would be to acknowledge the vulnerability of the sector to climate change and to integrate the sector's climate change adaptation plans into the national action plans for climate change adaptation. The critical question here is to determine whether it is enough to scale up the existing adaptation responses or if a transformational action is required to assure a climate-resilient development path. Synergies between climate mitigation goals –the massive introduction of renewables into the existing fossil fuel dominated energy mix– and climate adaptation efforts should be explored to increase the climate resilience of the sector.

Moreover, this dissertation has shown that the sector's adaptation to climate change has been reactive following weather and climate-related damages and losses. Ex-post adaptation focused on the extent and probability of past adverse events faces limitations in the climate-changed world. The expected increase in severity and probability of hazard events in a future climate calls for ex-ante strategies, especially when an expansion of the power system is considered. The future sector's resilience is co-developed today, requesting the integration of climate change projections, assessment of physical and economic impacts, and possible incremental or transformational adaptation responses (Kates et al., 2012) into the sector's long-term development plan.

Finally, given the adverse impact of climate change on the power sector, it is crucial for electric power utilities to include climate change adaptation into their long-term business strategies and capacity building. Increasing awareness of the power sector's stakeholders regarding climate change consequences for the sustainability of their business operations is an essential milestone.

Ensuring budget allocations for climate change mitigation and adaptation: In the context of Indonesia, achieving a 100% electrification ratio is a vital national development goal that affects human capital and other essential social and economic objectives. Therefore, electricity should be not only reliable but also affordable so that every citizen, including the poor, can enjoy electricity. To date, the government controls the electricity tariff and allocates subsidy for low-income households through the state electricity company. This subsidy is used to cover the difference between costs and the subsidized tariff for low-income households.

As discussed in Chapter 2 and Chapter 5, achieving the power sector's target under the Paris Agreement would add to the costs of electrification. Given that climate change is already affecting the power sector today due to past-emitted CO_2 and delayed mitigation actions, adaptation to climate change is unavoidable. Therefore, it is critical for the power sector to increase its resilience to climate change; for example, by taking ex-ante adaptation measures, such as investing in technology that is less vulnerable to climate change and upgrading electricity infrastructure. This would entail supplementary costs in addition to mitigation costs. Naturally, these additional costs could affect the electricity price and the size of the government subsidy. However, if climate change impacts and adaptations are considered at the early stages of electricity system expansion, it affects the choice of technology in the projected energy mix. This indicates that anticipatory climate change adaptation can bring co-benefits.

6.5. Limitations and the agenda for future research

While this dissertation makes a number of innovative contributions, it also opens doors for further research. Firstly, due to the scope of LEAP and data limitations, the power system expansion neglected constraints in the T&D networks, assuming that electricity can be transmitted at any time to any load station. Moreover, since the simulations in this doctoral research were carried out with an annual time-step over a long-term time horizon, hourly demand variations could not be accommodated due to computational feasibility. In this dissertation, the Java-Bali's load characteristics were divided into 48 time-slices, which represent four variations for each month (weekday, weekend, day, and night). Hence, the variations in demand were represented by a segmented load duration curve, making the temporal dynamic, such as continuous (hourly) variations in demand and intermittency and variability in supply, were ignored. Further modeling works will have to cover transmission capacity and spatial analysis of each power plant and substation, as well as include data on temporal characteristics of electricity demand and intermittency of renewable energy supply.

Secondly, with respect to ETL, this dissertation has taken into account the one-factor learning model, which relates technology costs with its cumulative capacity or production. An interesting extension could be to consider other factors, such as cumulative expenditure for research and development in the ETL simulations.

Thirdly, the quantifications of climate change impacts on the power system in this dissertation were preliminary, relying on the empirical data from several power plants and findings found in the literature. Further research may proceed with a systematic data collection to enable detailed estimations based on individual power plants, thereby enabling evaluating the site-specific impacts of climate change. Comparison of the empirical facts across power plants based on the same technology and across countries will allow for generalizations and estimation of probabilities and damage curves caused by the changing climate.

Finally, the integrated mitigation-adaptation modeling approach in this dissertation omitted the impacts of extreme weather events due to existing tools having a limited ability to capture extreme events (Cronin et al., 2018). While my fieldwork delivered data on both extreme events and gradual changes in climate variables, only the latter –i.e., increased air and seawater temperatures and changes in precipitation– were considered in the modeling part. Nonetheless, extreme events are expected to intensify under future climate change and will lead to physical infrastructure damages, energy losses, and indirect effects, such as business interruptions. Therefore, an important direction of future research would be to explore how extreme weather events would hinder long-term electrification and the climate change mitigation goals of the power sector due to damages and their social costs throughout the electricity value chain.

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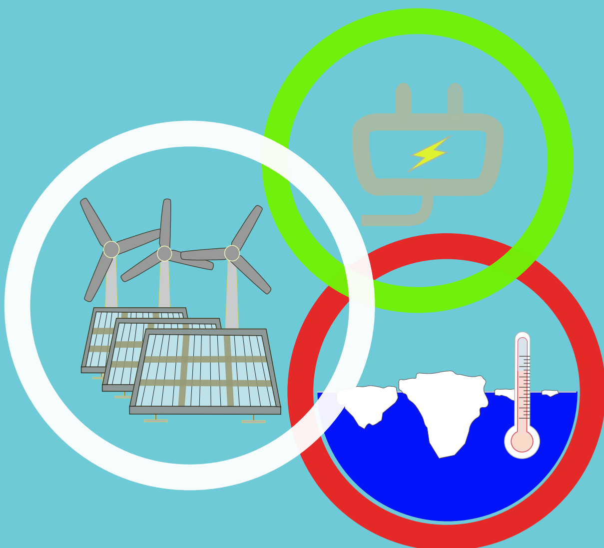
Appendices



Appendix 2.A: Systematic screening of energy models

Table 2A.1: Inventory of energy system models

		Suitability Criteria				
No.	**Model**	**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 (Connolly et al., 2010; Rosen and Rentz, 2007)	No	Yes	Yes	No	Yes
2	BALMOREL (Connolly et al., 2010; Ravn, 2001)	Yes	Yes	Yes	Yes	Yes
3	BHCP Screening Tool (Connolly et al., 2010; MacDonald and Fischer, 2007)	No	No	Yes	No	Yes
4	Compare Options for Sustainable Energy/COMPOSE (Connolly et al., 2010; Blarke, 2008)	No	Yes	Yes	Yes	Yes
5	E4cast (Connolly et al., 2010; Akmal et al., 2004)	Yes	Yes	Yes	Yes	Yes
6	Electricity Market Complex Adaptive Systems/EMCAS (North et al., 2002)	No	Yes	Yes	Yes	No
7	Early Market Introduction of New Energy Technologies/EMINEN (Connolly et al., 2010; Klemeš et al., 2009)	Yes	Yes	Yes	No	Yes

No	Model	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
8	EFI's Multi-Area Powermarket Simulator/EMPS (Connolly et al., 2010; Doorman et al., 2004)	Yes	Yes	Yes	Yes	Yes
9	EnergyPLAN (Lund, 2013)l	Yes	Yes	Yes	No	Yes
10	EnergyPRO (Connolly et al., 2010; EMD International A/S, 2017)	No	Yes	Yes	Yes	Yes
11	Energy and Power Evaluation Program/ENPEP-BALANCE (Connolly et al., 2010; CEEESA, 2017)	Yes	Yes	Yes	Yes	Yes
12	Generation and Transmission Maximisation Tool/GTMax (Connolly et al., 2010; Veselka, 2014)	No	Yes	Yes	Yes	No
13	H2RES (Connolly et al., 2010; Duić and da Graça Carvalho, 2004)	No	Yes	Yes	Yes	Yes
14	HOMER (Connolly et al., 2010; Lambert et al., 2006)	No	Yes	Yes	No	Yes
15	Hydrogen Energy Models/HYDROGEMS (Connolly et al., 2010; Ulleberg and Morkved, 2008)	No	Yes	Yes	No	Not clear*
16	IKARUS (Connolly et al., 2010; Martinsen et al., 2006)	Yes	Yes	Yes	Yes	Yes

No	Model	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
17	International Network for Sustainable Energy/INFORSE (Connolly et al., 2010)	Yes	Yes	Yes	Yes	Yes
19	Long-range Energy Alternative Planning System/LEAP (Heaps, 2017)	Yes	Yes	Yes	Yes	Yes
20	MARKet ALlocation model (MARKAL)/The Integrated MARKAL-EFOM System/TIMES (Loulou and Labriet, 2008)	Yes	Yes	Yes	Yes	Yes
21	Model for Energy Supply Strategy Alternatives and their General Environmental impact/MESSAGE (Connolly et al., 2010; Tot, 2012)	Yes	Yes	Yes	Yes	Yes
22	Mini Climate Assessment Model (MiniCAM)/Global Change Assessment Model/GCAM (The JGCRI GCAM Team, 2016)	Yes	Yes	Yes	Yes	Yes
23	National Energy Modelling System/NEMS (EIA, 2009)	Yes	Yes	Yes	Yes	Yes
24	Oak Ridge Competitive Electricity Dispatch/ORCED (Hadley, 2008)	Yes	Yes	Yes	Yes	Yes

No	Model	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
25	Programme-package for Emission Reduction Strategies in Energy Use and Supply-Certificate Trading/PERSEUS (Rosen and Rentz, 2007)	Yes	Yes	Yes	Yes	Yes
26	PRIMES (Mantzos and Capros, 1998)	Yes	Yes	Yes	Yes	Yes
27	ProdRisk (Connolly et al., 2010)	No	No	Yes	Yes	Not clear*
28	RAMSES (Connolly et al., 2010)	Yes	Yes	Yes	Yes	Yes
29	Renewable Energy Technology Screening Model/RETScreen (Connolly et al., 2010)	No	Yes	Yes	Yes	Yes
30	Simulation of Renewable Energy Networks/SimREN (Lehmann, 2003)	Yes	Yes	Yes	Yes	Not clear*
31	SIVAEL (Connolly et al., 2010)	No	No	Yes	No	Yes
32	Sustainable Technology Research and Energy Analysis Model/ STREAM (Risø, 2008)	Yes	Yes	Yes	Yes	Yes
33	TRNSYS16 (Solar Energy Laboratory University of Wisconsin-Madison, 2013)	No	No	Not clear*	Yes	Not clear*

No	Model	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
34	UniSyD3.0 (Connolly et al., 2010)	Yes	Yes	Yes	Yes	Yes
35	Wien Automatic System Planning Package/WASP (IAEA, 2006)	Yes	Yes	Yes	Yes	Yes
36	WILMAR Planning Tool (Meibom, 2005)	No	Yes	Yes	No	Yes
37	Regional Energy Scenario Generator/RESGEN (Foell et al., 1995)	Yes	Yes	Yes	Yes	No
38	Energy Flow Optimisation Model/EFOM (De Kruijk, 1994)	Yes	Yes	Yes	Yes	No
39	Prospective outlook on long-term energy systems/POLES (Enerdata, 2012)	Yes	Yes	Yes	Yes	Yes
40	World Energy Model/WEM (OECD/IEA, 2017)	Yes	Yes	Yes	Yes	Yes
41	System for the analysis of global energy markets/SAGE (DOE, 2003)	Yes	Yes	Yes	Yes	Yes
42	Electricity Generation Expansion Analysis System/EGEAS (Ng, 2015)	Yes	Yes	Yes	Yes	Yes
43	Asia-Pacific Integrated Model/AIM (AIM Project Team, 2016)	Yes	Yes	Yes	Yes	Yes
44	Atmospheric Stabilization Framework/ASF (IPCC, 2000)	Yes	Yes	Yes	Yes	Yes

No	Model	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
45	TARGETS-IMAGE Energy Regional Model/IMAGE-TIMER (De Vries et al., 2002)	Yes	Yes	Yes	Yes	Yes
46	Multiregional Approach for Resource and Industry Allocation/MARIA (IPCC, 2000)	Yes	Yes	Yes	Yes	Yes
47	PowerPlan (Benders, 1996)	Yes	Yes	Yes	Yes	Yes
48	Second Generation Model (SGM)/Phoenix (Wing et al., 2011)	Yes	Yes	Yes	Yes	Yes

*Unclear due to insufficient information

Table 2A.2: Accessibility of the suitable models

No	Tools	Accessibility	Link to free download
1.	Balmorel	Free*	http://www.balmorel.com/index.php/downloadmodel
2.	E4cast	Commercial	
3.	EMPS	Commercial	
4.	ENPEP-BALANCE	Free	Email to ceeesa@anl.gov
5.	H2RES	Internal use only	
6.	IKARUS	Commercial	
7.	INFORSE	Free to INFORSE members and cooperating European networks	
8.	LEAP	Free**	https://www.energycommunity.org/default.asp?action=download
9.	MARKAL/TIMES	Commercial	
10.	Mesap PLanet	Commercial	
11.	MESSAGE	Free***	
12.	MiniCAM/ GCAM	Free*	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

No	Tools	Accessibility	Link to free download
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*	http://www.globaloilwatch.com/reports/mdr-system-analysis-global-energy-markets-eia-082003.pdf
24.	EGEAS	Commercial	
25.	AIM	Free*	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*	http://www.globalchange.umd.edu/data/models/phx_documentation_august_2011.pdf

*The program is written in GAMS modeling language, which is a commercial software. **Free for students and non-profit institutions in developing countries. ***Free for academic purposes and the International Atomic Energy Agency (IAEA) member states.

Appendix 2.B: Input data for the LEAP Indonesian model 2005–2015

Table 2B.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	(58)
Discount rate	12%	Refers to the discount rate used by PLN

Table 2B.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 (PLN, 2005); [b]PLN Statistics 2005 (PLN, 2006)

Appendix 2.C: Input data for Java-Bali power system expansion 2016–2030

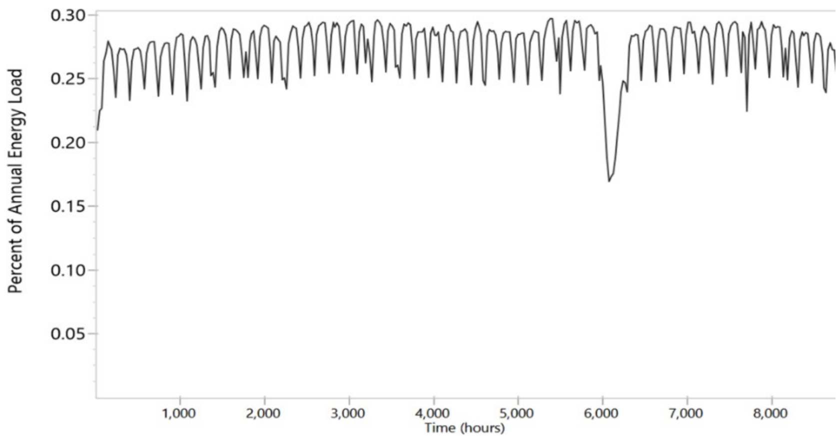


Fig. 2C.1: Load shape of the Java Bali power system (P2B, 2016a)

Table 2C.1: Power generation capacity of the Java-Bali Power System (P2B, 2016a)

Power plants	Net Capacity (MW)
Coal steam turbine	17,339
Natural gas combines cycle	8,971
Hydro	2,477
Geothermal	1,092
Natural gas open cycle	1066
Diesel generator	260
Natural gas engine	200
Total	31,405

Appendix 3.A: Input data for the LEAP simulations

3.A.1. Assumptions of Learning Rates

The assumptions of the initial learning rates are based on Rubin et al. (2015), as presented in Table 3A.1. They provide a review of learning rates from various studies. Due to the wide range of learning rate values presented in that study, here, I use the minimum, mean, and maximum values of the learning rate of each technology in this analysis (*REN-low LR*, *REN-medium LR*, and *REN-high LR*). In the case of hydropower, only one study is present in Rubin et al. (2015). Therefore, I use only one value for hydro in all three *REN LR* scenarios. Moreover, this secondary data specified a negative minimum learning rate value for nuclear, while its mean value is not provided. In this chapter, I assume the minimum learning rate value for nuclear is −6%, while the mean learning value for nuclear is assumed to be −1%, following the assumptions in Heuberger et al. (Heuberger et al., 2017). Since the learning rate for geothermal is not available, I assume it as 0% in all three scenarios.

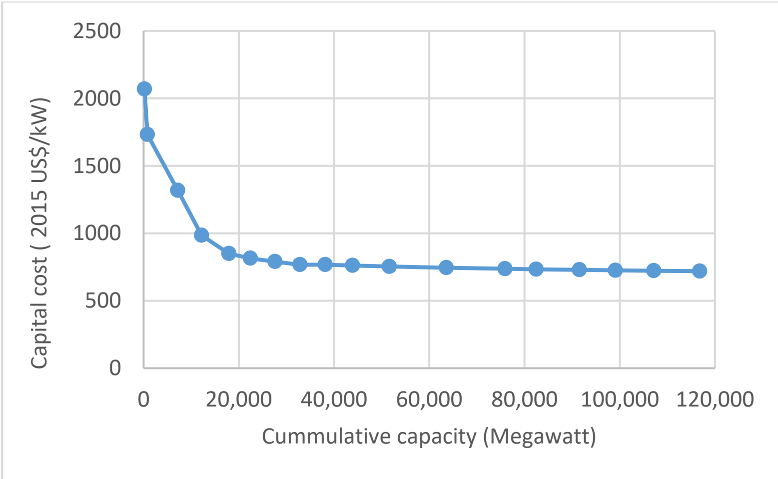
Table 3A.1: Learning rate values of power generation technologies (Rubin et al., 2015)

Technologies	**Learning Rates***			**Years covered across the studies**
	Minimum	**Mean**	**Maximum**	
Solar PV	10%	23%	47%	1959–2011
Wind Turbine	−11%	12%	32%	1979–2010
Biomass	0%	11%	24%	1976–2005
Pulverized coal	5.6%	8.3%	12%	1902–2006
Gas turbine	10%	15%	22%	1959–1990
NGCC	−11%	14%	34%	1980–1998
NGOC	10%	15%	22%	1958–1990
Hydro	1.4%	1.4%	1.4%	1980–2001
Nuclear	Negative	–	6%	1972–1996

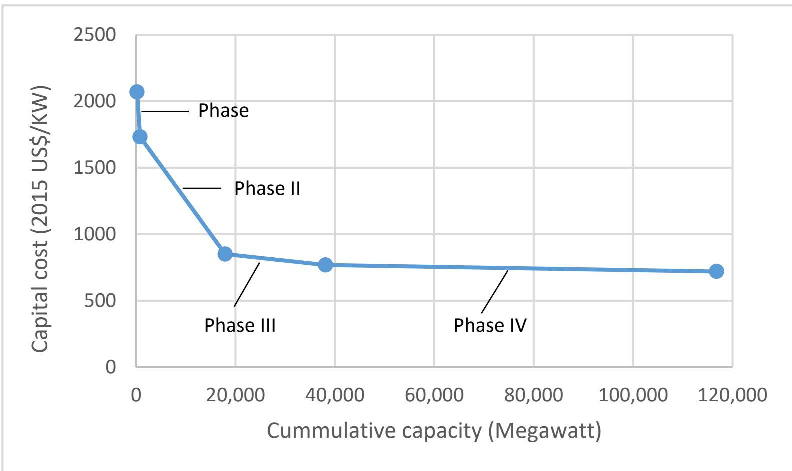
*The learning rate values are based on empirical data reported in the literature that were collected and reviewed by Rubin et al. (2015).

Appendix 3.B: Learning curves of solar PV

The optimization simulations in LEAP result in a massive deployment of solar PV in all three technological learning scenarios. Hence, the capital cost of solar PV reduced over time, as depicted in Fig. 3C.1 (for the *REN–medium LR* scenario). Fig. 3B.1 (a) shows a continues reduction in the capital cost of solar PV along with the increase in its cumulative capacity. As Fig. 3B.1 (b) illustrates, in Phases I and II, the cost reduction occurs faster. Meanwhile, in the later phases, the costs reduce slower partly because of the reduction in the learning rate value as well as the cumulative capacity already being high. In Phase II, the cumulative capacity reaches nearly 20 GW; thus, in Phase III, it requires another 20 GW of additional capacity to gain a 9% cost reduction, as assumed for the *REN–Medium LR* scenario (see Table 3A.1). Furthermore, in Phase IV, it requires another nearly 40 GW additional capacity to gain 4% of cost reduction.



(a)



(b)

Fig. 2C.1: Learning curves of solar PV assuming the medium value of the initial learning rate: (a) depicts a continuous cost reduction based on Eq. (9), while (b) depicts a linear approximation of the cost reduction in (a) that divides into four phases.

Appendix 4.A: Indonesia's vulnerability to climate change

Being a vast archipelagic country with 81,000 km of coastline and 42 million inhabitants living in low-lying areas, Indonesia is highly vulnerable to the adverse impacts of climate change (USAID, 2017). As many as 2,000 small islands are projected to sink by mid-century. Furthermore, by 2100, an estimate of 5.9 million people every year will be affected by coastal flooding. Other impacts of climate change include extended dry seasons, an increased frequency of extreme climate occurrences, and degraded biodiversity (BAPPENAS, 2014). A World Bank analysis ranks Indonesia 12th among 35 countries with high mortality risks due to multiple hazards, including climate-related hazards such as floods, landslides, and droughts (Dutch Sustainability Unit, 2016). Accordingly, an estimated 40% of Indonesians are at risk of various hazards, including earthquakes, tsunamis, volcanic eruptions, floods, landslides, droughts, and forest fires (World Bank, 2011). Table 4A.1 summarizes the trends and projections of the Indonesian climate.

Table 4A.1 Historical trends and future projections of the Indonesian climate. Source: (GERICS, 2015; USAID, 2017)

Climate parameters	Historical trends	Future projections
Temperature	Mean annual temperature increased 0.04° C per decade between 1985 to 2015	Mean annual temperature increase of 1.1 to 3.2° C by 2085
Heatwaves	The frequency of hot days and nights increased +88 days and +95 nights, respectively, since 1960.	- Increase in the duration of heat waves ranging from 23 to 1340 days by 2085 - The decrease in the duration of cold spell ranging from −10 to −1 day
Rainfall	Average annual rainfall increased by 12% from 1985 to 2015	- Although projections for rainfall differ, they point to increased rainfall during the wet season - A slight increase in the duration of dry spells (+2 days). - Increase in frequency and intensity of heavy rainfall events by 3–31% and 2–13%, respectively
Sea level	Sea level rise of 2–10 mm per year from 1993 to 2012	Sea level rise of 150–450 mm by 2056
Tropical glacier	Decreased of tropical Papua glaciers cover by 78% from 1936 to 2006	The disappearance of Papua glaciers

Appendix 4.B: Questionnaires and secondary data

Table 4B.1: List of questions for head office representatives

No	Questions	Expected supporting documents
1.	Based on your experience, how do weather and climate affect the power generation, transmission, and distribution networks?	
2.	Has flood ever occurred and affected the electricity infrastructure? How often? What was the cause? Did the infrastructure shut down? How much was the financial loss?	Documentation of the flood
3.	What has been done to deal with the floods? How much do these actions cost?	
4.	Were there any interruptions on electricity supply attributable to extreme weather? What and when? How much were the financial losses? How did the operation interruption affect the rest of the economy (in the region/island/country – choose the relevant)?	Documentation of operation interruptions due to extreme weather.
5.	Are there any policies and programs addressing climate change impact and adaptation? Is there any budget allocated?	Copy of policies and programs $$ of investments planned

Table 4B.2: List of questions concerning transmission networks

No	Questions	Expected supporting documents
1.	Has flood ever occurred in substations, and transmission networks? How often? What were the causes? Did they cause power cuts? How much were the financial losses?	Documentation of the flood SOP of dealing with floods
2.	What has been done to deal with the floods? How much do they cost?	
3.	Was there any operation interruption due to extreme weather? What and when? How often? How much was the financial loss?	Documentation of operation interruptions due to extreme weather
4.	Are there any policies and programs addressing climate change impact and adaptation? Is there any budget allocated?	Copy of policies and programs

Table 4B.3: List of questions for grid operator (load control center)

No	Questions	Expected supporting documents
1.	What is the load shape of the Java–Bali power system? In addition, Jakarta subsystem, West Java subsystem, Central Java subsystem, East Java subsystem and Bali subsystem.	At least ten years hourly–load data System Operation Evaluation Annual Reports (at least 10 years)
2.	Has flood ever occurred in the dispatcher units? How often? What were the causes? Did they cause power cuts? How much were the financial losses?	Documentation of the flood SOP of dealing with floods
3.	What has been done to deal with the floods? How much do they cost?	
4.	Was there any operation interruption due to extreme weather? What and when? How often? How much was the financial loss?	Documentation of operation interruptions due to extreme weather
5.	Are there any policies and programs addressing climate change impact and adaptation? Is there any budget allocated?	Copy of policies and programs

Table 4B.4: List of questions concerning distribution networks

No	Questions	Expected supporting documents
1.	Is there any information about the amount of electricity use for space cooling? Do you observe any trends in relationships between T rise and changes in demand for E (due to space cooling)?	
2.	Has flood ever occurred in distribution substations and networks? How often? What were the causes? Did they cause power cuts? How much were the financial losses?	Documentation of the flood SOP of dealing with floods
3.	What has been done to deal with the floods? How much do they cost?	
4.	Was there any operation interruption due to extreme weather? What and when? How often? How much was the financial loss?	Documentation of operation interruptions due to extreme weather
5.	Are there any policies and programs addressing climate change impact and adaptation? Is there any budget allocated?	Copy of policies and programs

Table 4B.5: List of questions concerning hydropower plants

No	Questions	Expected supporting documents
1.	What is the trend of precipitation and water level? Has the water level changed from the first year of operation?	Monitoring data of precipitation, water inflow, the water level
2.	How does the trend affect electricity production?	Monitoring data on electricity production
3.	Was there any operation interruption due to low water level/drought or excessive water? How often? How much were the financial losses?	Water level and electricity production data
4.	Have there been any actions done to increase the water level? What are they? How much do they cost?	
5.	Has flood ever occurred in the power plants? How often? What was the cause? Did the plant shut down? How much was the financial loss?	Documentation of the flood SOP of dealing with floods
6.	What has been done to deal with the floods? How much do they cost?	
7.	Was there any operation interruption due to extreme weather? What and when? How often? How much were the financial losses?	Documentation of operation interruptions due to extreme weather
8.	Are there any company's policies and programs addressing climate change impact and adaptation? Is there any budget allocated?	Copy of policies and programs

Table 4B.6: List of questions concerning thermal power plants (coal- and gas-based power plants)

No	Questions	Expected supporting documents
1.	What is the trend of cooling water temperature?	Monitoring data on cooling water temperature in last (5, 10, 15 years if possible)
2.	Is there any correlation between cooling water temperature and power plant efficiency? What and how?	Monitoring data on cooling water temperature and power plant's efficiency
3.	Has the sea level changed from the first year of operation?	Sea level data
4.	What has been done to maintain the cooling water temperature at the desired level? How much does it cost? To what extent (in %?) were you able to recover the power output to the pre-warming levels?	
5.	Has flood ever occurred and affected the power plants? How often? What was the cause? Did the plant shut down? How much was the financial loss?	Documentation of the flood
6.	What has been done to deal with the floods? How much do these actions cost?	
7.	Was there any operation interruption due to extreme weather? What and when? How much were the financial losses?	Documentation of operation interruptions due to extreme weather.
8.	Are there any policies and programs addressing climate change impact and adaptation? Is there any budget allocated?	Copy of policies and programs $$ of investments planned

Appendix 4.C: Historical data of hydroelectric power plants

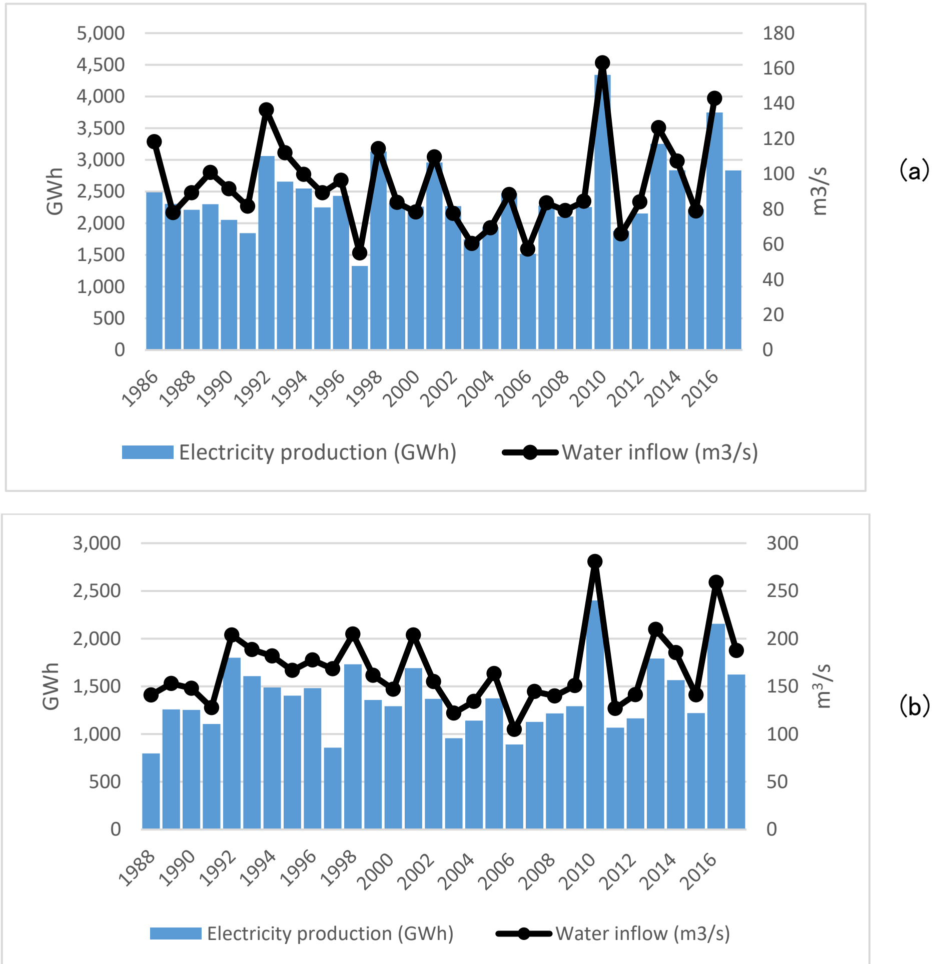
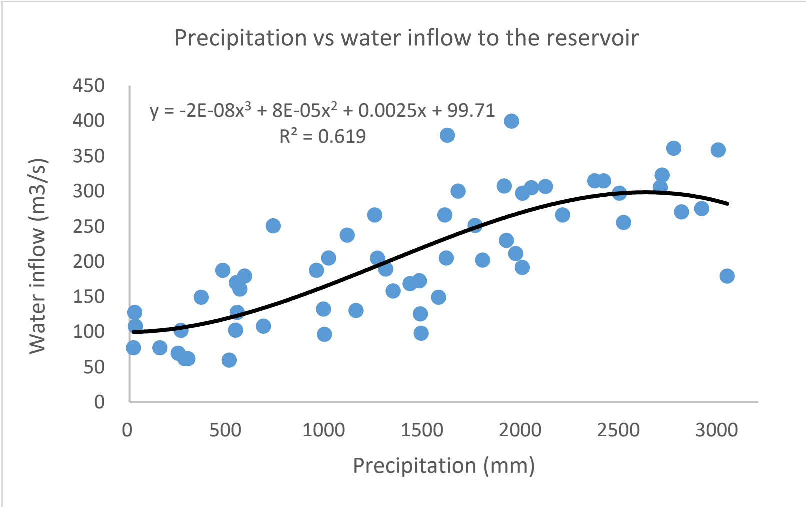
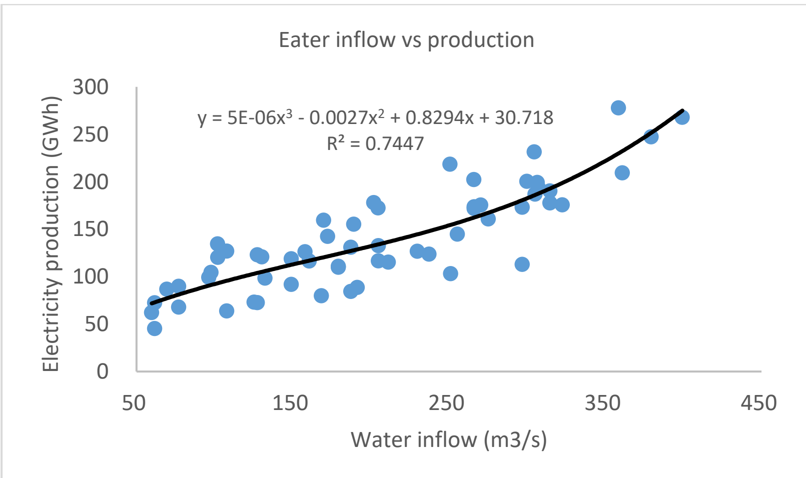


Fig. 4C.1: Historical data on electricity production and water inflow Saguling HEPP (a) and Cirata HEPP (b). Source: own fieldwork.



(a)



(b)

Fig. 4C.2: Correlation between precipitation, water inflow, and electricity production: Cirata HEPP 2013–2017. (a) Monthly water inflow as a function of precipitation[15]; (b) Monthly electricity production as a function of water inflow. Source: own analysis.

[15]Precipitation data from seven weather stations

Appendix 5.A: Projection of temperature and precipitation changes

Table 5A.1: Historical and projected changes in temperature

Month	Temperature (°C)				
	1986–2005	Projected changed			
		2020–2039		2040–2059	
		RCP4.5	RCP8.5	RCP4.5	RCP8.5
January	25.88	0.69	0.76	1.03	1.37
February	25.94	0.73	0.82	1.09	1.45
March	26.22	0.72	0.81	1.06	1.40
April	26.43	0.75	0.83	1.05	1.42
May	26.41	0.71	0.82	1.07	1.43
June	26.05	0.72	0.81	1.07	1.45
July	25.73	0.73	0.84	1.06	1.42
August	25.74	0.71	0.82	1.07	1.41
September	25.92	0.77	0.82	1.10	1.43
October	26.20	0.77	0.83	1.09	1.43
November	26.21	0.74	0.84	1.09	1.41
December	25.95	0.69	0.79	1.02	1.39

Table 5A.2: Historical and projected changes in temperature

Month	Precipitation (mm)				
	1986–2005	Projected changed			
		2020–2039		2040–2059	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
January	336.73	18.08	9.42	29.90	20.87
February	266.76	−3.62	4.48	0.52	14.48
March	343.74	0.83	15.38	15.36	15.56
April	327.12	−5.28	4.32	10.43	13.86
May	240.61	−6.10	−1.65	−0.06	1.48
June	115.71	−3.43	−7.23	−0.25	−3.47
July	109.90	−8.02	−7.95	−10.32	−17.47
August	101.13	−1.69	−0.22	−6.22	−3.98
September	137.69	−4.24	−2.18	−2.16	−6.87
October	287.00	−8.80	−9.24	−7.22	−10.95
November	398.00	1.99	8.53	13.27	4.36
December	340.32	−1.83	−8.89	15.28	−5.09

Appendix 5.B: Assumptions for projecting climate change impacts on the electricity supply

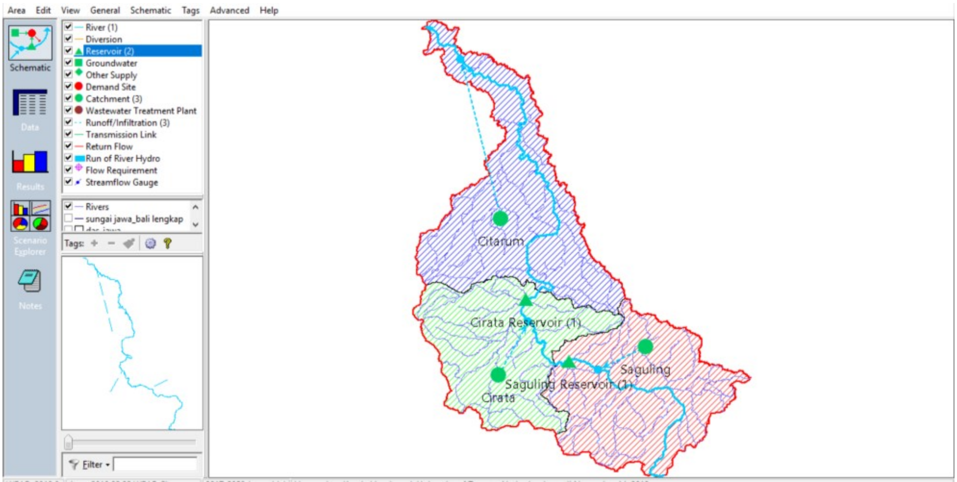
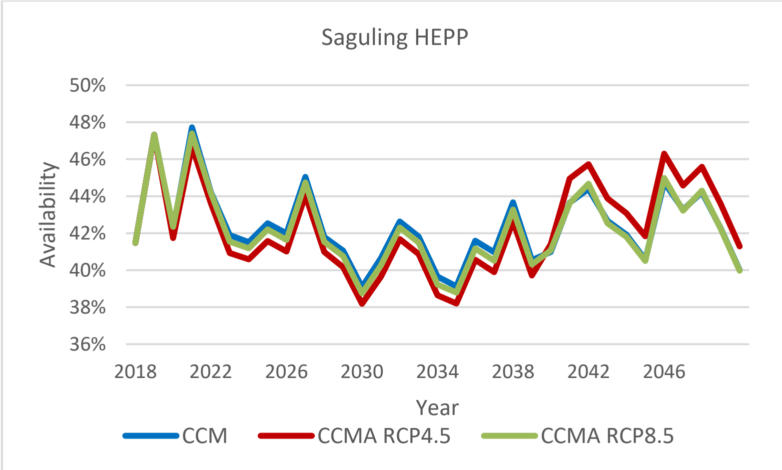


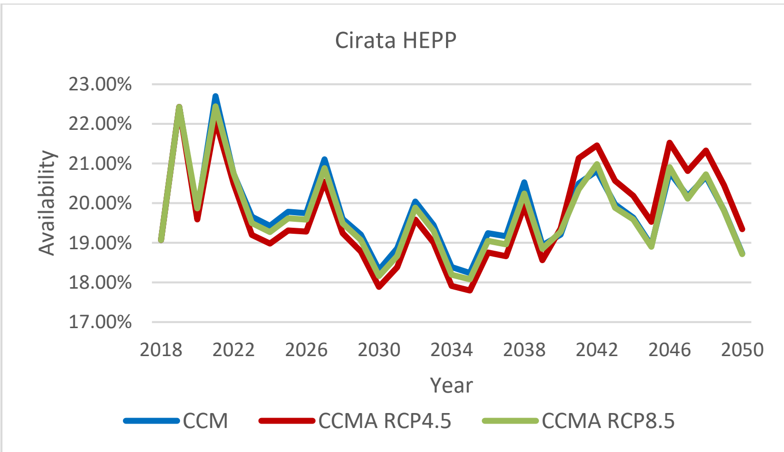
Fig. 5B.1: Schematic view of water demand and supply of the Citarum WEAP model. Source: own simulations

Table 5B.1: Input data for the Citarum WEAP model

Input Data	**Value**	**Sources**
Catchment		
Map	Fig. 5B.2	KLHK (KLHK, 2011), BIG (BIG, 2017b)
Area	Saguling: 222,000 ha Cirata: 416,000 ha	Own calculation based on geospatial analysis
Precipitation (mm)	Monthly, 1948–2010 Monthly, 1986–2017	Sheffield et al. (Sheffield et al., 2006) PLTA Cirata (PLTA Cirata, 2018) and PLTA Saguling (PLTA Saguling, 2018)
Temperature (° C)	Mean monthly air temp, 1948–2010	Sheffield et al. (Sheffield et al., 2006)
Wind speed (m/s)	Monthly, 1948–2010	Sheffield et al. (Sheffield et al., 2006)
Total Storage Capacity		PLTA Cirata (PLTA Cirata, 2018)
Cirata	2,165 million m^3	
Saguling	875 million m^3	PLTA Saguling (PLTA Saguling, 2018)
Max Turbine Flow		
Cirata	1,080 m^3/s	PLTA Cirata (PLTA Cirata, 2018)
Saguling	219.2 m^3/s	PLTA Saguling (PLTA Saguling, 2018)
Tailwater Elevation		Kasiro et al. (Ibnu Kasiro, Isdiana, D. Pangluar, CL Nugroho, Attan Muchtar, Hari Martadi, 1995)
Cirata	84 m	
Saguling	252 m	



(a)



(b)

Fig. 5B.2: The average annual capacity factor of HEPPs under CCM and CCMA scenarios: Saguling HEPP (a); Cirata HEPP (b). Source: WEAP estimates.

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Summary

Electricity is the backbone of the modern world. Yet, an electricity connection is beyond the reach of nearly one billion people worldwide. While the global power sector is expanding to meet the increasing electricity demand, global warming calls for its transformation to a low-carbon sector. Under the Paris Agreement, countries have committed to curbing carbon emissions, with the power sector being one of the primary targets for emissions reduction actions. At the same time, climate change is affecting the global economy, including the power sector, and hence the power sector needs to be greener and climate-resilient.

The goal of this dissertation is to address the above societal problem by assessing the triple nexus of electrification, climate change mitigation, and climate change adaptation in the power sector of developing countries, taking Indonesia as an example. This goal is pursued by employing a set of methodological steps, including modeling with the LEAP and WEAP software tools and extensive data collection through interviews and FGDs with stakeholders from different stages of the power sector supply chain. This dissertation gradually advances the current modeling practice by sequentially taking into consideration endogenous technological learning as well as climate change impacts and adaptation.

Chapter 2 investigates plausible trade-offs between electrification and climate change mitigation in Indonesia's primary power system – i.e., Java-Bali. Accordingly, Indonesia's NDC pledge is included in the simulation of the power system expansion. Results indicate that the national electrification and the Paris Agreement goals can be achieved through switching from coal to natural gas and renewable energy. The CO_2 mitigation scenario requires 5% – 7% of additional costs compared to the reference (electrification only) scenario. Meanwhile, the cost-effectiveness of CO_2 mitigation scenarios ranges from 36.3 and 46.6 US$/t$CO_2$e.

Chapter 3 extends the LEAP modeling practice by incorporating technological learning to assess the diffusion of renewable energy in the Java-Bali power system in Indonesia. The chapter indicates that endogenous technological learning accelerates the penetration of renewable energy and lowers the costs of achieving Indonesia's renewable energy targets. Furthermore, at the medium and high pace of technological learning, the total costs of electricity production to achieve the long-term renewable energy target are 4-10% lower than the scenario without considering technological learning.

Chapter 4 moves the discussions to the climate change adaptation challenge. This chapter presents the empirical evidence of the impacts of severe weather events and gradual changes in climate variables on all segments of Java-Bali's electricity supply chains: generation, transmission, and distribution. Weather- and climate-related disruptions cause financial losses for the electric utilities due to damaged equipment and energy-not-supplied. Accordingly, utilities take autonomous adaptation measures, which include behavioral, managerial, and technological responses.

Finally, Chapter 5 brings together the triple objectives of electrification, climate change mitigation, and climate change adaptation within the LEAP modeling framework. The results show that the joint objectives alter the future technology mix when compared to the electrification-only scenario. Moreover, there is an increase in the installed capacity and electricity generation to balance the climate-induced rise in electricity demand and to compensate for the reduction in power-generating capacity under adverse impacts of the future climate. As a result, the total costs of power capacity expansion increase significantly.

This dissertation provides a number of innovative contributions to science. Firstly, to the best of our knowledge, it is the first to assess the implications of the Indonesian NDC for the power sector, using a bottom-up energy system model. Hence, it adds to the literature on balancing the electrification and climate change mitigation goals. Secondly, it is the first to integrate endogenous technological learning into the LEAP model, thereby advancing the LEAP methodology and adding understanding regarding the role of technological learning in driving the transition from fossil-fuel-based power generation to a lower-carbon power system. Thirdly, it presents historical evidence of the vulnerability of the Indonesian power sector to climate variability and change, which is likely to be shared among other developing countries. Hence, it adds to the scarce literature on climate change impacts, adaptation, and vulnerability in developing countries. Finally, it explicitly connects the objective of the power sector's climate change mitigation goal with the interferences caused by the impact of climate change on the sector. This dissertation, therefore, contributes to filling the gap in the literature on integrated analysis of climate change mitigation and adaptation in the energy sector highlighted by IPCC AR5.

On the practical side, this dissertation offers several policy implications. First, the deployment of the currently unexploited renewable energy should be started as early as possible to gain benefits of technological learning and avoid further technological lock-ins of fossil-fuel-based technologies. Accordingly, the conditions that facilitate faster local-learning should be made available to reduce the costs of renewable energy technologies even more quickly. Second, it is essential that the acceleration of renewable energy deployment go hand-in-hand with the improvement of the grid capacity, which includes technical and human capital capacities. Third, the power sector's vulnerability to climate change should be acknowledged at the national level, and its adaptation plans should be integrated into the national action plans for climate change adaptation. Likewise, it is crucial for electric utilities to include climate change adaptation into their long-term business strategies and capacity building. Finally, the power sector needs to ensure budget allocations for climate change mitigation and adaptation to realize a future low-carbon, climate-resilient power sector.

Samenvatting

Elektriciteit is een ruggengraat van de moderne wereld. Toch is een elektriciteitsvoorziening buiten bereik van bijna een miljard mensen wereldwijd. Terwijl de mondiale elektriciteitssector groeit om tegemoet te komen aan de toenemende vraag naar elektriciteit, vraagt de opwarming van de aarde om transformatie naar een koolstofarme sector. In het kader van de overeenkomst van Parijs hebben landen zich ertoe verbonden de koolstofemissies te reduceren, waarbij de elektriciteitssector een van de belangrijkste partijen is. Tegelijkertijd treft de klimaatverandering de mondiale economie, met inbegrip van de elektriciteitssector. Ook daarom moet de energiesector groener en klimaatbestendig zijn.

Het doel van dit proefschrift is na te gaan hoe het bovengenoemde maatschappelijke probleem kan worden aangepakt. De verweving tussen elektrificatie, mitigatie van klimaatverandering en aanpassing aan de klimaatverandering in de elektriciteitssector van ontwikkelingslanden wordt beoordeeld, waarbij Indonesië als voorbeeld wordt genomen. Ik streef dit doel na door een reeks methodologische stappen te zetten, waaronder het modelleren met de LEAP-en WEAP-software tools en uitgebreide gegevensverzameling via interviews en interviews met belanghebbenden uit verschillende stadia van de toeleveringsketen van de elektriciteitssector. In opeenvolgende hoofdstukken modeleer ik de praktijk, rekening houdend met endogene technologische leerprocessen en aanpassing van de klimaatverandering.

In Hoofdstuk 2 worden plausibele afwegingen tussen elektrificatie en mitigatie van klimaatverandering in het belangrijkste energiesysteem van Indonesië – d.w.z. Java-Bali onderzocht. Het kader daarbij is de belofte van Indonesië om koolstofemissie te reduceren en tevens groei van het energiesysteem om aan de vraag voor elektriciteit te voldoen. De resultaten geven aan dat de nationale elektrificatie en de doelstellingen van de Overeenkomst van Parijs kunnen worden bereikt door over te schakelen van steenkool naar aardgas en hernieuwbare energie. Het CO2-beperkingsscenario vereist 5% – 7% extra kosten in vergelijking met het referentiescenario (alleen elektrificatie). Ondertussen varieert de kosteneffectiviteit van CO2-beperkende scenario's van USD 36,3 and 46,6 per tCO_2e.

In Hoofdstuk 3 breid ik de LEAP-modellering uit door technologisch leerproces op te nemen. Vooral diffusie van hernieuwbare energie in het Java-Bali energiesysteem in Indonesië wordt beoordeeld. Het hoofdstuk geeft aan dat endogeen technologisch leerproces de verspreiding van hernieuwbare energie versnelt en de kosten van het behalen van de beoogde duurzame energie in Indonesië versnelt. Bovendien zijn de totale kosten van elektriciteitsproductie om het langetermijndoel voor hernieuwbare energie te halen bij het gemiddelde en hoge tempo van technologisch leren 4% tot 10% lager dan het scenario zonder rekening te houden met technologisch leerproces.

In Hoofdstuk 4 worden de discussies naar de aanpassing aan de klimaatverandering verschoven. Onderbouwd worden de effecten van drastische weersveranderingen en geleidelijke klimaatsveranderingen op alle segmenten van de stroomvoorzieningsketens van Java-Bali: opwekking, transmissie en distributie. Storingen verbonden met de weer- en klimaatsveranderingen veroorzaken financiële verliezen bij de elektriciteitsbedrijven als gevolg van beschadigde apparatuur en niet-geleverde energie. Dienovereenkomstig nemen nutsbedrijven aanpassingsmaatregelen in het gedrag, bestuur en technologie.

Ten slotte worden in hoofdstuk 5 de drievoudige doelstellingen van elektrificatie, beperking van de klimaatverandering en aanpassing aan de klimaatverandering gemodelleerd met behulp van LEAP. De resultaten laten zien dat bij klimaatdoelstellingen de toekomstige technologiemix veranderd in vergelijking met het scenario met alleen elektrificatie. Bovendien is er een toename van de geïnstalleerde capaciteit en elektriciteitsopwekking om de door het klimaat veroorzaakte stijging van de vraag naar elektriciteit te dekken en de vermindering van de elektriciteitsproductiecapaciteit te compenseren. Als gevolg hiervan nemen de totale kosten van de hogere capaciteit aanzienlijk toe.

Dit proefschrift levert een aantal innovatieve bijdragen aan de wetenschap. Ten eerste, voor zover wij weten, is het de eerste keer dat de gevolgen van de Indonesische Nationale klimaatdoelstellingen voor de energiesector zijn beoordeeld met behulp van een bottom-up model voor het Indonesische energiesysteem. Daarom draagt het onderzoek bij aan de literatuur over het balanceren van de doelstellingen voor elektrificatie en de beperking van de klimaatverandering. Ten tweede is het de eerste keer dat technologische leerproces endogeen in het LEAP-model is geïntegreerd. Daardoor wordt de LEAP-methodiek verbeterd en begrip wordt vergroot over de rol van het technologisch leerproces bij de overgang van energieopwekking op basis van fossiele brandstoffen naar een koolstofarm energiesysteem. Ten derde presenteert het historisch bewijs van de kwetsbaarheid van de Indonesische elektriciteitssector voor klimaatvariabiliteit en verandering, die waarschijnlijk ook bij andere ontwikkelingslanden veel voorkomt. Daarom draagt het bij aan de schaarse literatuur over de gevolgen van klimaatverandering, aanpassing en kwetsbaarheid in ontwikkelingslanden. Ten slotte worden de doelstellingen van de energiesector om de klimaatverandering te verminderen met interventies van de elektriciteitssector en gevolgen van klimaatsveranderingen voor de sector. Dit proefschrift draagt daarom bij aan het opvullen van de leemte in de literatuur over geïntegreerde analyse van de koolstofemissiereductie en aanpassing aan klimaatverandering in de energiesector.

Het proefschrift toont diverse implicaties voor de beleidspraktijk. Ten eerste moet de inzet van de momenteel onbenutte hernieuwbare energie zo snel mogelijk worden gestart om de voordelen van technologisch leren te behalen en verdere technologische "*lock-ins*" van de nieuw te installeren infrastructuur voor de op fossiele brandstoffen gebaseerde elektriciteitsproductie te voorkomen. Dienovereenkomstig moeten de voorwaarden worden geschapen om een sneller leerproces door te maken waarmee de kosten van technologieën voor hernieuwbare energie nog sneller worden beperkt. Ten tweede is het van essentieel belang dat de versnelling in de inzet van hernieuwbare energie gepaard gaat met de verbetering van de netcapaciteit, waaronder technische en menselijke capaciteiten. Ten derde moet de kwetsbaarheid van de energiesector voor klimaatverandering op nationaal niveau worden erkend en moeten de aanpassingsplannen van de sector worden geïntegreerd in de nationale actieplannen voor aanpassing aan de klimaatverandering. Evenzo is het van cruciaal belang voor elektriciteitsbedrijven om aanpassing aan de klimaatverandering op te nemen in hun langetermijnstrategieën en opbouw van hun capaciteit. Ten slotte moet de energiesector zorgen dat er voldoende begroting beschikbaar is voor de klimaatmitigatie en aanpassing van de klimaatverandering waarmee ze een toekomstige koolstofarme en klimaatbestendige energiesector kan realiseren.

Ringkasan

Tenaga listrik merupakan tulang punggung kehidupan modern. Namun, masih terdapat hampir satu milyar populasi bumi belum memiliki sambungan listrik. Oleh karena itu, sektor ketenagalistrikan di seluruh dunia, khususnya di negara-negara berkembang berekspansi dalam rangka memenuhi permintaan listrik yang meningkat. Di sisi lain, isu pemanasan global menyerukan sektor ketenagalistrikan untuk bertransformasi menuju sektor yang rendah karbon. Di bawah kerangka Perjanjian Paris, negara-negara bersepakat untuk membatasi emisi karbon, dan pada umumnya mengikutsertakan upaya penguranagn emisi di sektor ketenagalistrikan. Sementara itu, dampak perubahan iklim telah dirasakan oleh ekonomi global saat ini, termasuk sektor ketenagalistrikan. Oleh karena itu, di masa yang akan datang, sektor ketenagalistrikan tidak hanya dituntut untuk lebih bersih, tetapi juga lebih tahan terhadap dampak perubahan iklim.

Tujuan dari disertasi ini adalah untuk memberikan kontribusi solusi terhadap permasalahan di atas dengan melakukan kajian mengenai keterkaitan tiga tujuan penting sektor ketenagalistrikan, yaitu: elektrifikasi, mitigasi perubahan iklim, dan adaptasi terhadap dampak perubahan iklim. Pencapaian tujuan ini diupayakan dengan menggunakan serangkaian metodologi, termasuk pemodelan dengan perangkat lunak LEAP dan WEAP dan melakukan pengumpulan data melalui wawancara serta diskusi kelompok secara terarah dengan para pemangku kepentingan dari berbagai elemen rantai pasokan penyediakan tenaga listrik. Disertasi ini secara bertahap memperbaharui LEAP dengan secara bertahap memasukan pertimbangan "endogenous technological learning" dan adaptasi sistem ketenagalistrikan terhadap perubahan iklim.

Bab 2 menyajikan evaluasi beberapa skenario trade-off antara elektrifikasi dan mitigasi perubahan iklim di sistem ketenagalistrikan Jawa-Bali. Dalam hal ini, target penurunan emisi sektor energi Indonesia yang tercantum dalam dokumen *Nationally Determined Contribution* (NDC) dijadikan pertimbangan dalam simulasi pengembangan sistem ketenagalistikan

Jawa–Bali. Hasil simulasi menunjukkan bahwa target elektrifikasi dan NDC dapat dicapai melalui peralihan energi primer pembangkit listrik dari batubara ke gas alam dan energi terbarukan. Skenario mitigasi CO_2 tersebut membutuhkan biaya tambahan 5% – 7% dibandingkan dengan skenario dasar yang hanya mempertimbangkan target elektrifikasi. Sementara itu, efektifitas biaya mitigasi CO_2 berkisar antara USD 36,3 and 46,6/tCO_2e.

Pada Bab 3, metode kalkulasi biaya pada perangkat lunak LEAP dimodifikasi dengan memasukkan formula "endogenous technological learning" dalam rangka mengkaji penetrasi energi terbarukan dalam sistem ketenagalistrikan Jawa–Bali. Bab ini menyimpulkan bahwa "endogenous technological learning" mempercepat penetrasi energi terbarukan dalam sistem ketenagalistrikan Jawa–Bali dan mampu menurunkan biaya pencapaian target energi terbarukan Indonesia. Lebih jauh lagi, pada skenario "technological learning" dengan kecepatan sedang dan tinggi, total biaya produksi listrik untuk mencapai target energi terbarukan jangka panjang menjadi 4% – 10% lebih rendah dibandingkan skenario tanpa mempertimbangkan "technological learning".

Pada Bab 4, pembahasan disertasi ini dialihkan ke topik adaptasi perubahan iklim. Bab ini membahas dampak kejadian cuaca buruk dan perubahan variabel iklim pada proses bisnis penyediaan tenaga listrik di sistem Jawa–Bali yang meliputi: pembangkitan, transmisi, dan distribusi. Berdasarkan hasil wawancara dengan pemangku kepentingin penyediaan tenaga listrik dan hasil kajian terhadap laporan gangguan pembangkit, transmisi, dan distribusi, dapat disimpulkan bahwa gangguan terkait cuaca dan iklim telah menyebabkan kerugian finansial untuk perusahaan–perusahaan penyedia tenaga listrik akibat peralatan yang rusak dan energi listrik yang tidak tersalurkan. Perusahaan–perusahaan penyedia tenaga listrik telah mengambil langkah–langkah adaptasi terhadap kejadian cuaca buruk dengan melakukan upaya–upaya teknis dan manajerial.

Bab 5 menyatukan tiga tujuan penting yaitu: elektrifikasi, mitigasi perubahan iklim, dan adaptasi terhadap dampak perubahan iklim dalam kerangka pemodelan LEAP. Hasil penelitian menunjukkan bahwa ketika ketiga tujuan tersebut dipertimbangkan dalam simulasi pengembangan sistem ketenagalistrikan Jawa-Bali, maka bauran teknologi di masa depan mengalami perubahan jika dibandingkan dengan skenario dasar yang hanya mempertimbangkan elektrifikasi. Selain itu, diperlukan pula penambahan kapasitas terpasang pembangkit dan produksi listrik untuk memenuhi kenaikan permintaan listrik yang disebabkan oleh kenaikan suhu akibat perubahan iklim serta untuk mengkompensasi penurunan keandalan pembangkit listrik akibat dampak perubahan iklim. Hal-hal tersebut menyebabkan total biaya ekspansi sistem ketenagalistrikan meningkat secara signifikan.

Disertasi ini memberikan beberapa kontribusi inovatif bagi ilmu pengetahuan. Pertama, sejauh pengetahuan kami, disertasi ini adalah yang pertama melakukan kajian implikasi target penurunan emisi sektor ketenagalistrikan Indonesia di bawah Perjanjian Paris dengan menggunakan model bottom-up. Oleh karena itu, disertasi ini menambah literatur terkait energi dan perubahan iklim. Kedua, disertasi ini merupakan kajian pertama yang mengintegrasikan "endogenous technological learning" ke dalam model LEAP, sehingga ada pembaharuan metodologi LEAP dan menambah pemahaman tentang peran "technological learning" dalam mendorong transisi dari energi listrik berbasis bahan bakar fosil ke energi rendah karbon. Ketiga, disertasi ini menyajikan bukti historis kerentanan sektor tenaga listrik Indonesia terhadap variabilitas dan perubahan iklim, yang juga mewakili kerentanan negara-negara berkembang lainnya. Oleh karena itu, disertasi ini menambah literatur yang masih terbatas mengenai dampak perubahan iklim, adaptasi, dan kerentanan di negara-negara berkembang. Keempat, disertasi ini secara eksplisit menggabungkan tujuan mitigasi dan adaptati perubahan iklim di sektor ketenagalistrikan sehingga berkontribusi untuk mengisi kesenjangan literatur tentang analisis terpadu mitigasi dan adaptasi perubahan iklim di sektor energi sebagaimana ditekankan dalam Laporan Kajian IPCC ke-5.

Disertasi ini juga menawarkan beberapa rekomendasi kebijakan yang dapat diterapkan. Pertama, pemanfaatan energi terbarukan yang saat ini belum dieksploitasi harus dimulai sedini mungkin untuk mendapatkan manfaat "technological learning" dan menghindari ketergantungan pada teknologi berbasis bahan bakar fosil. Selain itu, kondisi yang dapat memfasilitasi "local learning" perlu diupayakan agar penurunan biaya teknologi energi terbarukan dapat terjadi lebih cepat. Kedua, percepatan pemanfaatan energi terbarukan harus berjalan seiring dengan penguatan kapasitas sistem ketenagalistrikan, yang mencakup kapasitas teknis dan sumber daya manusia. Ketiga, kerentanan sektor energi terhadap perubahan iklim perlu diarusutamakan di tingkat nasional, dan rencana adaptasinya harus diintegrasikan ke dalam rencana aksi nasional adaptasi perubahan iklim. Demikian juga, sangat penting bagi perusahaan penyedia tenaga listrik untuk memasukkan adaptasi perubahan iklim ke dalam strategi bisnis jangka panjang dan program penguatan kapasitas. Terakhir, sektor ketenagalistrikan perlu mengalokasikan anggaran untuk mitigasi dan adaptasi perubahan iklim dalam rangka mewujudkan infrastruktur ketenagalistrikan yang rendah karbon dan tahan terhadap dampak perubahan iklim.

About the Author

Kamia Handayani was born in Garut, Indonesia. She holds a Master of Science (Cum Laude) in Energy & Environmental Management from the University of Twente, the Netherlands, and a Bachelor of Environmental Engineering from Bandung Institute of Technology, Indonesia. After working for a decade at PT PLN (Persero), the state-owned electric power company in Indonesia, she took a study leave in 2016 to pursue a doctoral degree at the Department of Governance and Technology for Sustainability, University of Twente, the Netherlands.

Kamia represented the University of Twente at the UN Climate Change Conference COP23 in Bonn (2017). She also shared a panel with resourceful people in COP24 in Katowice (2018), which included the Dutch climate envoy and various young experts. She has presented her works at numerous international conferences and regularly writes articles for The Jakarta Post.

During her previous service in PLN, Kamia contributed to the development of a system for evaluating the environmental management performances of PLN business units all over Indonesia. She also involved in the development of climate change mitigation strategies of the company. Kamia's expertise includes carbon credit for clean energy projects and environmental & social safeguards for electricity infrastructure projects, among others. She is a member of numerous energy and environmental communities, including the International Association for Energy Economics (IAEE), European Association of Environmental and Resources Economists (EAERE), Southeast Asian Women, 4TU Centre for Resilience Engineering (4TU RE), Energy Academy Indonesia (Ecadin), and Yayasan Pembangunan Berkelanjutan-LEAD Indonesia. She is a volunteer at 'Indonesia Mengglobal' and 'I Care Indonesia' and the coordinator of Komunitas Hijau PLN (PLN Green Community).

List of Publications

Journal articles

1. **Handayani, K.**, Filatova, T, Krozer, Y., & Anugrah, P. (2019). Seeking for climate change mitigation and adaptation nexus: Analysis of a long-term power system expansion. Applied Energy. (Under review).
2. **Handayani, K.**, Filatova, T., & Krozer, Y. (2019). The Vulnerability of the Power Sector to Climate Variability and Change: Evidence from Indonesia. *Energies*, *12*(19), 3640.
3. Gonella, F., Almeida, C. M. V. B., Fiorentino, G., **Handayani, K.**, Spanò, F., Testoni, R., & Zucaro, A. (2019). Is technology optimism justified? A discussion towards a comprehensive narrative. Journal of cleaner production, 223, 456-465.
4. **Handayani, K.**, Krozer, Y., & Filatova, T. (2019). From fossil fuels to renewables: An analysis of long-term scenarios considering technological learning. Energy Policy, 127, 134-146.
5. **Handayani, K.**, Krozer, Y., & Filatova, T. (2017). Trade-offs between electrification and climate change mitigation: An analysis of the Java-Bali power system in Indonesia. Applied energy, 208, 1020-1037.

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1. **Handayani, K.**, Filatova, T., Krozer, Y., & Anugrah, P. (2019). Toward a low-carbon and climate-resilient power system: A case of the Indonesian power sector. Paper presented at 42nd IAEE International Conference, Montreal, Canada.
2. **Handayani, K.**, Krozer, Y., & Filatova, T. (2017). Assessment of renewable energy expansion in the Java-Bali islands, Indonesia. In S. Ulgiati, L. Vanoli, M. T. Brown, M. Casazza, & H. Schnitzer (Eds.), 10th Biennial International Workshop Advances in Energy Studies: Energy futures, environment and well-being (pp. 271). TU Graz.
3. **Handayani, K.**, Krozer, Y. (2014). Cost-effectiveness of emission reduction for the Indonesian coal-fired power plants. The 20th Conference of Electric Power Supply Industry, International Convention Center Jeju, South Korea.

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1. Linking climate change mitigation and adaptation: An integrated power system expansion modeling. EMP-E conference 2019: Modelling the implementation of A Clean Planet For All Strategy. 8-9 October 2019, Brussels, Belgium.
2. Exploring young-led climate partnership towards COP25: 'What we have brought from COP24 Katowice 2018', 27 February 2019, The Indonesian embassy, The Hague, the Netherlands.
3. Young Professionalism in climate resilience, UN Climate Change Conference (COP24), 14 December 2018, Katowice, Poland.
4. Panel Discussion: How to create societal support for alternative energies. 31 August 2018, University of Twente, the Netherlands.
5. Simulasi Pencapaian Target Penurunan Emisi Gas Rumah Kaca Sektor Ketenagalistrikan, Webinar Energy Academy Indonesia, 29 October 2017.
6. Opportunities for Climate Change Mitigations: A Case Study of the Indonesian Power Sector. International Symposium on Sustainability Science, "Understanding Climate Change Phenomena for Human Well Being", 8-10 September 2014, Bandung, Indonesia.
7. Renewable Energy for Electrification in Flores Island, Indonesia. ICREP Conference: "Improving energy Access through Climate Finance: Picking the Winners", 26-28 March 2013, Enschede, the Netherlands.

Media articles

1. Kamia Handayani (2018). Invest in 'Technology Cost Learning'. The Jakarta Post, 08 November. http://www.thejakartapost.com/academia/2018/11/08/invest-in-technology-cost-learning.html
2. Kamia Handayani (2017). Securing electricity supply: Climate change does matter. The Jakarta Post, 26 October. http://www.thejakartapost.com/academia/2017/10/26/securing-electricity-supply-climate-change-does-matter.html
3. Kamia Handayani (2016). Trading off electrification and climate change. The Jakarta Post, 28 October. http://www.thejakartapost.com/academia/2016/10/28/trading-off-electrification-and-climate-change.html

Electricity is the backbone of the modern world. Yet, an electricity connection is beyond the reach of nearly one billion people worldwide, making electrification a vital development objective.

While the global power sector is expanding to meet the increasing electricity demand, global warming calls for its transformation to a low-carbon sector. Under the Paris Agreement, countries have committed to curbing carbon emissions, with the power sector being one of the primary targets for emissions reduction actions.

At the same time, climate change is affecting the global economy, including the power sector. Extreme weather event is among the primary causes of power outages, which will likely intensify under future climates. Gradual changes in climate variables also threaten the power sector's reliability.

The question is then: "How could the power sector balance the triple objectives of electrification, climate change mitigation, and climate change adaption?"