TOWARD A LOW CARBON AND CLIMATE RESILIENT POWER SYSTEM: A CASE OF THE INDONESIAN POWER SECTOR

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1. Overview

One in five people on the planet today still lacks access to electricity (United Nations Development Programme, 2018). Hence, ensuring universal access to energy services is a vital goal for the power sector worldwide. However, this goal has to be aligned with another pivotal global ambition: curbing climate change. Moreover, while the power sector becomes the target for reducing global carbon emissions, the sector itself is vulnerable to the adverse impacts of the changing climate. Climate change affects the power sector in two ways: through acute, disruptive, severe weather events and gradual long-term changes in climate parameters (Sieber, 2013).

This paper aims to analyze the interplay between three goals –electrification, climate change mitigation, and climate change impact and adaptation– taking the Indonesian power sector as a case study. The country strives to achieve near-universal electricity access by 2020 (Government of The Republic of Indonesia, 2014). While today the country's electricity supply relies heavily on fossil fuels, it pledges to reduce its carbon emissions by 29% in 2030 (Government of The Republic of Indonesia, 2016). Meanwhile, the electricity supply in the country is often interrupted by severe weather events (PLN Yogyakarta, 2015), which promise to be even more frequent and severe in the climate-changed world. We address this problem by providing a framework for an integrated analysis of electrification, climate change mitigation, and climate change adaptation for developing a low-carbon and climate-resilient power system.

2. Methodology and data

To address the nexus between electrification, climate mitigation, and climate adaptation ambitions, we employ a mix of methods. This approach allows us to integrate both climate change mitigation and adaptation into the analysis of long-term power sector development in Indonesia (Fig. 1, left-hand flow). We use these methods within the framework of electrification as foreseen by the Indonesian policy. For the mitigation part, we develop a long-term scenario for the power sector development taking into account the country's low-carbon development policy. Subsequently, we use the Long-range Energy Alternative Planning System (LEAP), an energy system model developed by the Stockholm Environment Institute (SEI), to analyze the electrification & climate mitigation scenarios.

Furthermore, since climate impacts and adaptation to them are local, we need to find data to setup parameters for integrating climate change impact and adaptation into LEAP. We take a 3 step approach here (Fig. 1, right-hand flow). Firstly, we carry out an extensive fieldwork by visiting ten major power plants in Indonesia between February-March 2018. We collected data on the impacts (in energy not supplied, monetary costs) of extreme weather (e.g., heavy precipitations and heavy winds) as well as gradual pressures such as changes in precipitation patterns. We also hold interviews to explore the responses of electric power utility to the adverse impacts. Secondly, we do an extensive literature review on downscaling climate scenarios to identify the likely trends in temperature and precipitation for the Indonesian archipelago. Thirdly, we identify the variables and functions in the LEAP model architecture to parameterize the possible climate impacts and adaptation response of the Indonesian electricity sector. We focus on three major power plant types namely coal-fired power plant (CFPP), natural gas power plant (NGPP), and hydroelectric power plant (HEPP). For the HEPP, we use the Water Evaluation and Planning System (WEAP), which was also developed by SEI, to analyze the impacts of future climate change on water availability for hydroelectric power plants. In summary, we rely on findings from our fieldwork and on the current literature to parameterize the impacts of future climate change on thermal power plants (TPPs).

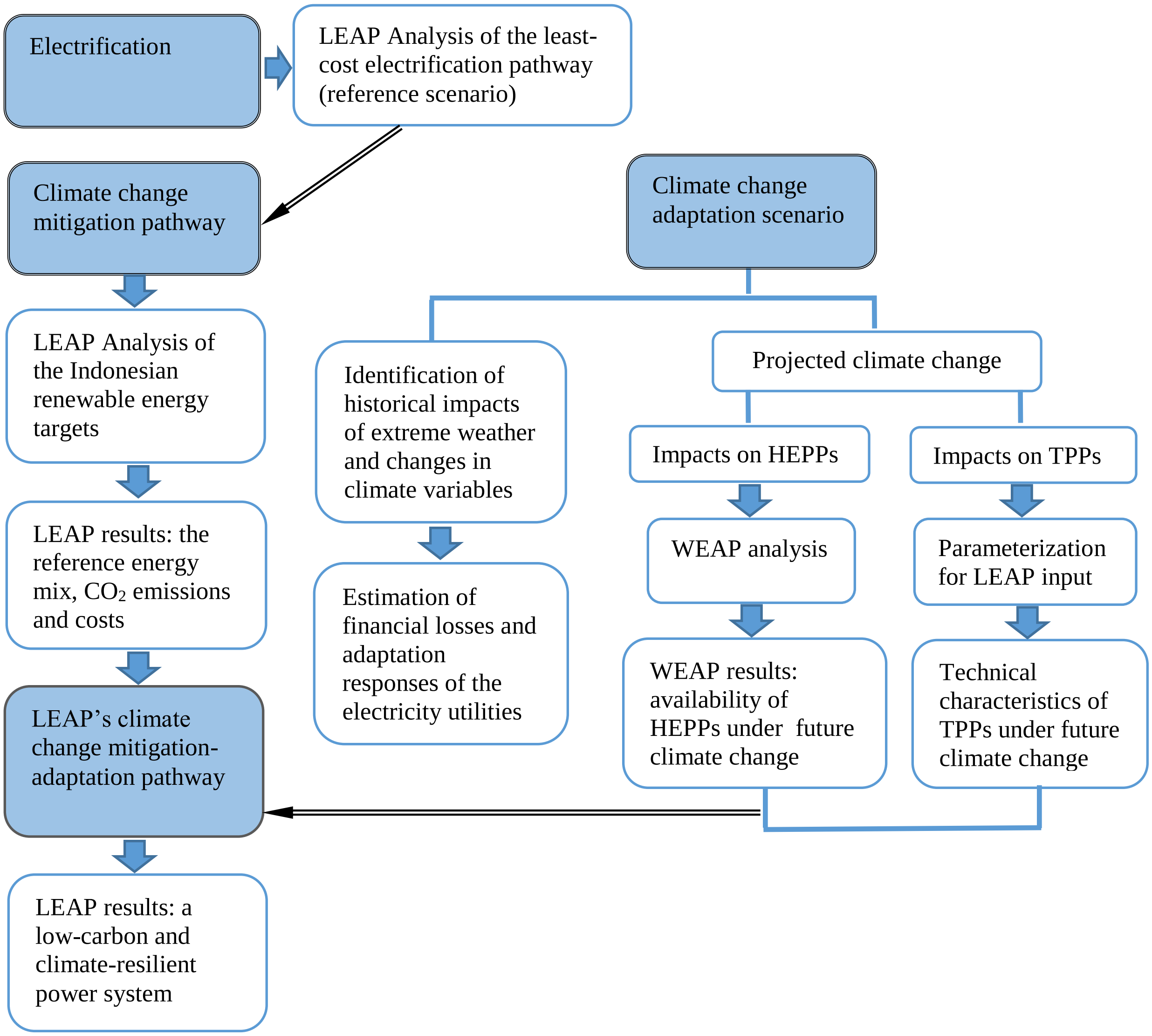

Fig. 1 Conceptual framework for integrating climate change mitigation and adaptation into the LEAP model

2.1. LEAP setup for analyzing the electrification and low carbon scenarios

In this study, we focus on the Java-Bali power system, which comprises 75% of Indonesian electricity consumption (PLN, 2017) and serves 59% of the Indonesian populations (BPS, 2010). Moreover, the Java-Bali mirrors Indonesia's power sector in term of the historical energy mix, supply, and demand (Handayani, Krozer and Filatova, 2019). Firstly, we develop a reference scenario, i.e., the electricity expansion scenario without considering climate change. Hence, the objective of this scenario is solely to satisfy the future demand for electricity in Java-Bali islands, employing LEAP's least-cost optimization. LEAP optimizes power capacity expansion based on total costs over the time horizon of the study. The methodology of the Java-Bali LEAP model is explained in details in (Handayani, Krozer and Filatova, 2019). This study updates the previous one by including the most recent historical data of energy demand and supply. Accordingly, the LEAP base year is updated from 2015 to 2017. Furthermore, we update the electricity demand projection in accordance with the latest electricity development plan (PLN, 2018). 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).

Furthermore, we add alternative scenarios, which include low carbon and climate-resilient pathways. The low carbon pathway refers to the country's policy of increasing the share of renewable energy in the national energy mix up to 23% by 2025 and 31% by 2050. Hence, we set up the LEAP horizon until 2050 putting the renewable energy targets as constraints of the simulations. This scenario serves as the climate mitigation scenario, where we assume the future development of the Java-Bali power system shifts to a low carbon path, yet neglecting the sector's adaptation to climate change for now.

2.2. Integrating climate change impacts into LEAP

2.2.1. Identification of weather and climate effects on power generation

We identify the actual effects of severe weather and changes in climate variables on the Indonesian electricity sector based on the data that were collected through an extensive fieldwork and reviews of utilities' internal reports as well as published energy sector information. The fieldwork included interviews, site visits, and focus group discussions (FGD) with ten power plants, one load control center, two transmission offices, and two distribution offices, involving 51 participants. The selected power plants consist of coal-fired power plants, natural gas power plants and hydroelectric power plants – the three major power plant's types in Indonesia – spread throughout Java and Bali islands (Table 1, and Fig. 2). In total, the ten power plants represent 35%[1] of total power generation capacity in the Java-Bali electricity grid.

Prior to conducting the fieldwork, we developed a questionnaire for guiding the interviews and FGDs, which included questions about the occurrence of power plants' disruptions due to weather and climate and how the utilities respond and adapt to those disruptions.

Table 1 Indonesian power plants where primary data collection has taken place.

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

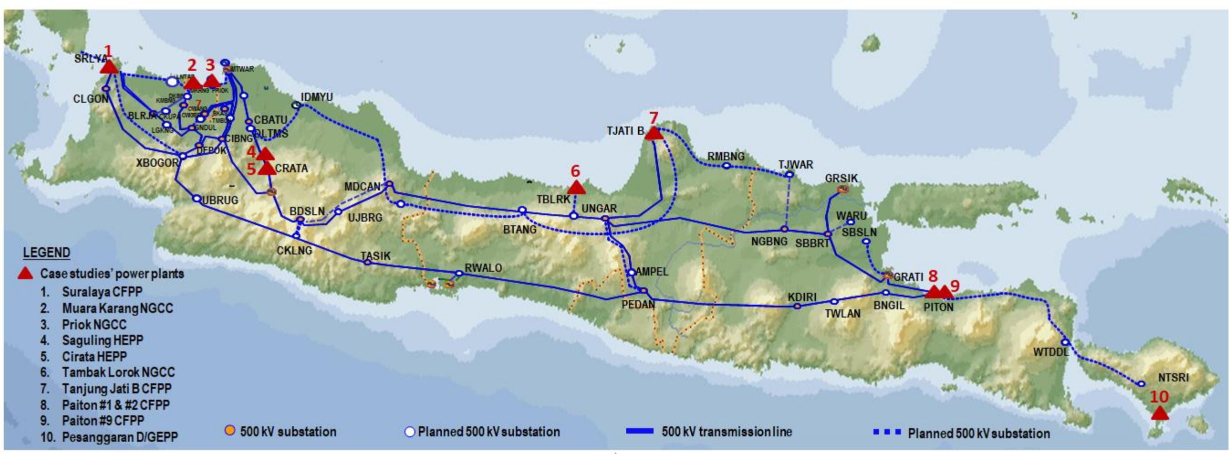

Fig. 2 Locations of power plants where data collection has taken place, modified from PLN (2018).

2.2.2. Projections of future climate change

For the climate change scenarios, we refer to projections from the Southeast Asia Climate Analysis and Modelling Framework (SEACAM). SEACAM downscaled data from six global climate change models to generate high-resolution (25 km) climate change projection for Southeast Asia up to the year 2100 (Rahmat *et al.*, 2014). These projections are based on the A1B scenario of the IPCC special report on emission scenarios (SRES) with two time slices: 2031-2060 and 2071-2100 compared to the baseline period of 1970-2000. To fill the data gap of temperature changes from 2018 through to 2030, we refer to World Bank (2011), which projects an increase in temperature ranging from 0.2°C to 0.3°C per decade. Meanwhile, the precipitation changes during the same period were interpolated from the available climate projection data.

[1] Calculated based on KESDM (2017) and PLN (2017)

2.2.3. Accounting for climate change impacts in LEAP

As a bottom-up energy model, LEAP allows setting detailed characteristics of energy technologies in its input data. In this paper, we identify the pathways to translate climate change impacts and potential adaptation actions into the changes in technical characteristics of electric power technologies. We rely heavily on our fieldwork as well as on the literature reporting downscaled climate change scenarios. We focus mainly on CFPPs, NGPPs, and HEPPs as they constitute most of the Indonesian power generation capacity, i.e., 50%, 28%, and 9%, respectively.

3. Results

3.1. Electrification and climate change mitigation: LEAP results

3.1.1. Least-cost Electrification

The demand for electricity in Java-Bali islands is projected to increase over fivefold from around 175 TWh in 2017 to 904 TWh in 2050. Consequently, the electricity generation from power plants – which also accounts for own consumption and transmission losses – increases at the same pace i.e., 982 TWh in 2050, compared to 182 TWh in 2017. Concerning the primary energy use, the electricity mixes in 2025 and 2050 mirror that in the base year (2017) (see Fig 3). In 2050, electricity generation from coal keeps dominant in the electricity mix, followed by natural gas, hydro and geothermal. Hence, there is no significant change in the deployment of energy resources and technologies.

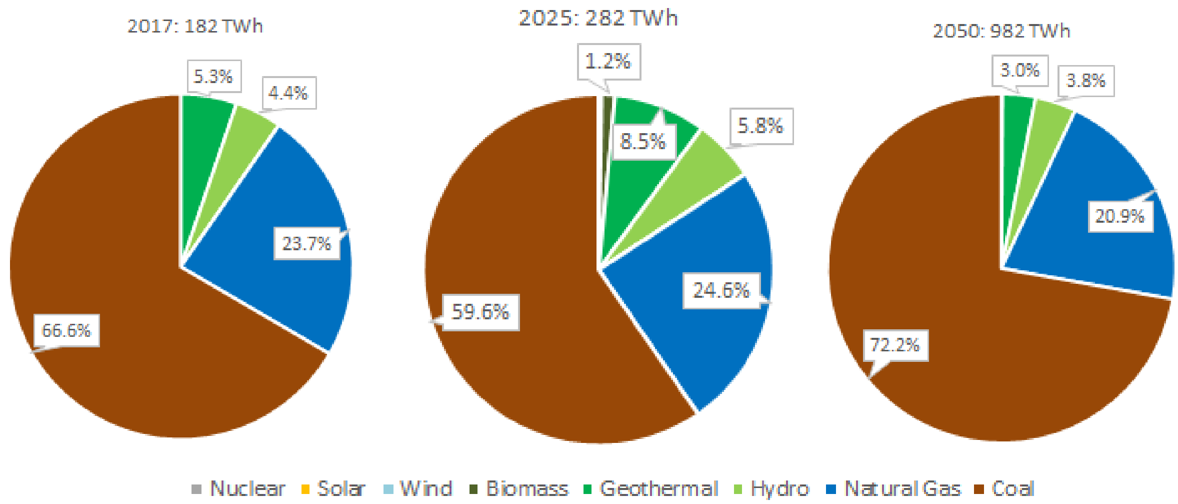

Fig. 3 The Java-Bali electricity mix in 2017, 2025, and 2050

3.1.2. A low-carbon power sector development

While fossil fuels served most of the demand for electricity in the base year, under the low-carbon pathway scenario, they gradually reduce their share in the Java-Bali electricity mix. Renewables compose 23% and 31% of the electricity mix by 2025 and 2050, respectively (see Fig. 4). Accordingly, there is a significant change in the deployment of energy resources and technologies where biomass, solar, and wind now appear in the electricity mix.

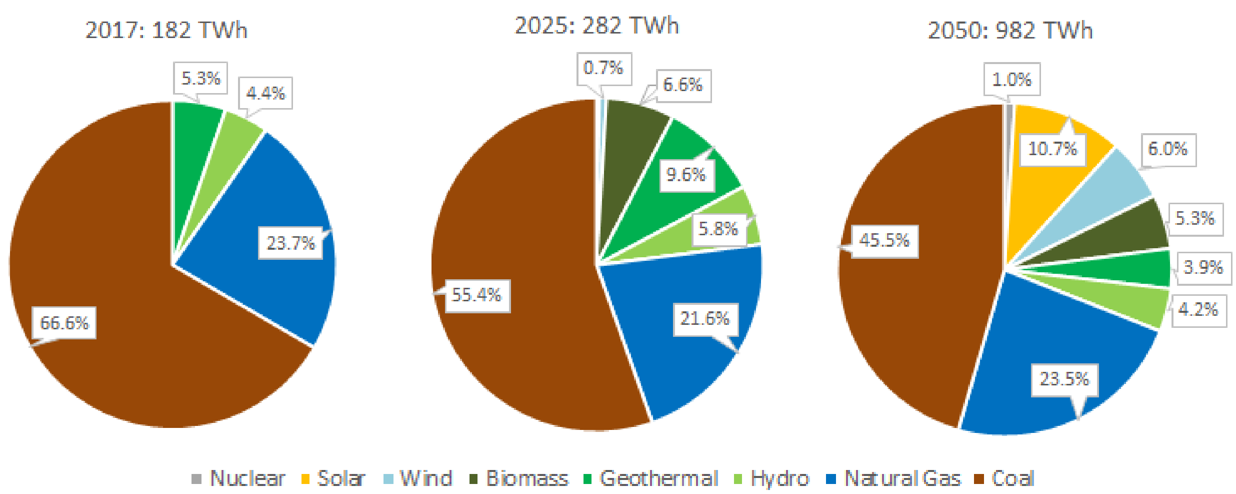

Fig. 4 The Java-Bali electricity mix in 2017, 2025, and 2050

3.1.3. CO_2 reduction and cost implication

The increased deployment of renewable energy in the low-carbon scenario results in a reduction in cumulative CO_2 emissions of the Java-Bali power system (Fig. 5). By 2025 and 2050, the cumulative CO_2 emissions under the low-carbon scenario are 3% and 23% lower, respectively compared to the reference scenario (least-cost electrification scenario). The low- carbon scenario involves an estimated 76.6 billion USD of total costs by 2050 (Fig. 6), which is 8% higher compared to that in the reference scenario.

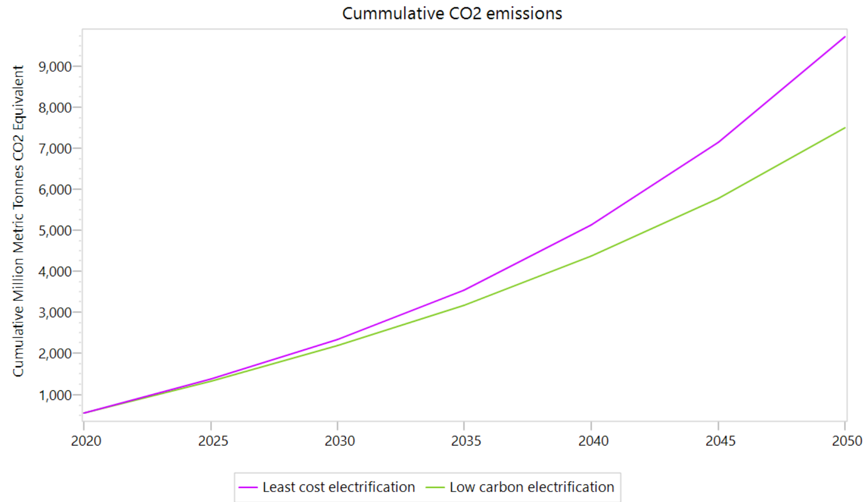

Fig. 5 Cumulative CO_2 emissions over the study period

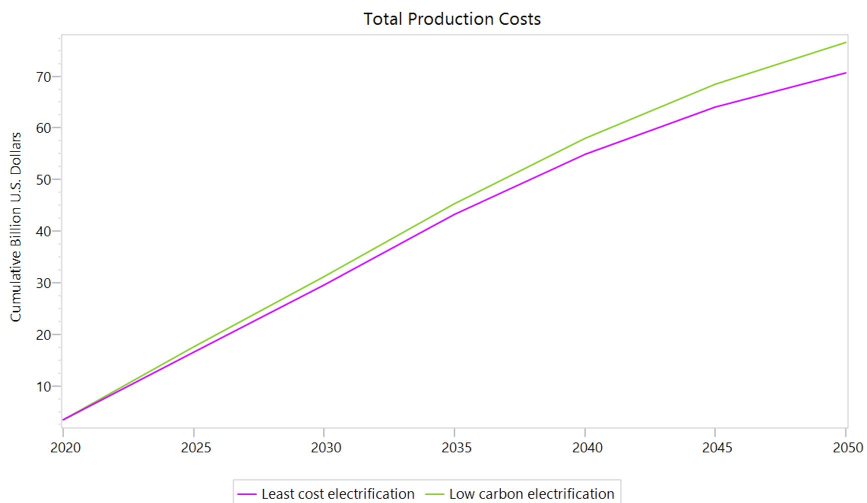

Fig. 6 Total production costs over the study period

3.2. Historical evidence and future impacts of climate change

3.2.1. Identified impacts and adaptation responses

Based on the fieldwork and reviews of internal power plants documents, we identified a number of effects of severe weather and changes in climate variables on power generation as described in Table 2. Severe weather and changes in climate variables affect the power generation. So far, in Indonesia, severe weather mainly affects fuel coal quality and stock of CFPPs and cooling water supply in CFPPs and NGPPs. Heavy precipitation often reduces coal quality causing reductions in the power plant's capacity factor. Extreme events also cause direct monetary losses for electric power utilities, such as the case of jellyfish inflow in 2016, which forced Paiton#9 to shut down for 20 days, causing an estimated financial loss of 21.3 million USD for the utility. Meanwhile, gradual climate change such as changes in precipitation patterns affect HEPPs' operation. Furthermore, our fieldwork confirms that ambient air temperature influences the power output of NGPPs.

To some extent, utilities have implemented adaptation actions in response to severe weather. These actions encompass behavioral, managerial and technological responses. The technological responses include investment in the flood control system in power plants and the application of weather modification technology to create artificial rain to increase water inflow to HEPPs' reservoirs. Behavioral and managerial responses include alteration of coal shipment contract, increase in routine checking of distribution networks in anticipation of the approaching rainy season, and modification of HEPP's operation pattern plan.

Table 2 Impacts of severe weather and changes in climate variables on the Indonesian power sector

Severe event	Identified impacts
Heavy precipitation	- Heavy precipitation can turn a significant amount of dry coal into wet coal, making the burning efficiency lower and thus reducing the power output. Moreover, wet coal causes plugging in the coal feeder resulting in further reduction in power output; - An increase in river flow due to heavy precipitation brings more waste into the sea, which impedes the power plant's water uptake; - Heavy precipitation that lasts for days leads to high water inflow to the hydropower reservoir. This situation can cause water spills from the reservoir, increasing the risk of flooding downstream; - Heavy precipitation can cause floods;
Heavy wind and high sea waves	Interruptions in coal shipping jeopardize the fuel coal stock of coal-fired power plants (CFPPs), which leads to a reduction of power generation capacity or even a shutdown of power plants;
Jellyfish inflow	Jellyfish can clog in the circulating water pump of coastal thermal power plants causing a reduction in the power generation capacity or even a plant shutdown;
Heatwave	Warm ambient air temperature affects the efficiency of gas turbine and gas/diesel engine power plants;
Drought	Very low water inflow causes a significant decrease in power generation capacity;
Sea level rise	The increase in sea level rise causes coastal flooding affecting coastal power plants;
Seawater temperature	An increase in seawater temperature affects the efficiency of the cooling water system.

3.2.2. Future climate change scenarios

Based on our literature review of downscaled climate change projections for Indonesia, we identify scenarios of temperature and precipitation changes relevant to the Indonesian electricity sector (see Table 3). Concerning the temperature changes, the SEACAM results are uniform between all models with the average annual temperature rise ranging from 2°C to 3°C in 2031-2060. Contrarily, the precipitation change projections vary between models. In this study, we take into account extreme precipitation changes in each season, which include both reduction and intensification in precipitations compared to the baseline period. Accordingly, we develop scenarios for those extreme situations taking into account combination in changes of the two climate variables (see Table 4).

Table 3 Projection of future changes in temperature and precipitation for Indonesia as compared to 1971-2000 period (Rahmat et al., 2014; World Bank, 2011)

Future time slice	Temperature changes (°C)		Precipitation changes (%)	
	Minimum	Maximum	Minimum	Maximum
2001-2030	+0.2 per decade	+0.3 per decade	-10	+14
2031-2060	+2	+3	-20	+29

Table 4 Climate change scenarios

Scenarios	Description
T_{low} $P_{decrease}$	Temperature increases by 2 degrees, seasonal precipitations decrease up to 20%
T_{low} $P_{increase}$	Temperature increases by 2 degrees, seasonal precipitations increase up to 29%
T_{high} $P_{decrease}$	Temperature increases by 3 degrees, seasonal precipitation decreases up to 20%
T_{high} $P_{increase}$	Temperature increases by 3 degrees, seasonal precipitations increase up to 29%

3.2.3. Modeling climate change impacts and adaptations in LEAP

Referring to the identified effects of climate change as discussed in Section 3.2.1, we identify the most detrimental effects and transform them into changes in technical characteristics of power plants. The changed technical characteristics include capacity factor and or efficiency of the respective power plants (de Lucena, Schaeffer and Szklo, 2010; Asian Development Bank, 2012; Anugrah *et al.*, 2015). These changes are expected to influence the energy resource/technology mix and installed capacity, and reflect the costs of climate change and benefits of adaptation. Table 5 lists climate change impacts on three types of power plants to be integrated into the LEAP model.

Table 5 Accounting for climate change adaptation in the LEAP Model

Climate change impacts on power generation	Source of impact	Technical characteristics to be adjusted in LEAP
Reduction in power output of the natural gas turbine	Increase in surface air temperature	Capacity factor
Changes in water availability for hydroelectric power plants	Changes in precipitation and temperature	Capacity factor
Reduction in the efficiency of the cooling water system in thermal power plants due to increased temperature of inlet cooling water	Increase in seawater temperature	Efficiency
Reduction in power output of coal-fired power plants due to the wet coal	Increased precipitations	Capacity factor

3.2.4. Ongoing work

This is a work in progress. Our next step is to quantify the effects of climate change on power plants, given the downscaled climate change scenarios, into the changes in technical characteristics for the LEAP input data. We use different approaches to parameterizing the effects of future climate change on thermal power plants (i.e., CFPPs and NGPPs) and HEPPs. For TPPs, we will estimate the impacts of climate change based on historical evidence and extrapolate the data following the projected climate change. Meanwhile, we will use WEAP for quantifying the impact of climate change on hydropower production. WEAP is a software tool that can be used among others to simulate water demand, supply, flow, storage, discharge, and pollution. One of the methodological considerations of WEAP is the use of scenario analyses to answer what-if questions related to water demand and supply. Furthermore, WEAP has a built-in capability with LEAP where the hydropower availability modeled by WEAP becomes an input for LEAP. Hence, the use of both software packages enables a dynamic analysis of climate change implications on hydropower production (Spalding-fecher, 2018). The WEAP methodology is described in details in Sieber (2019) and Yates et al. (2005).

4. Conclusions

The power sector contributes to climate change and is simultaneously, affected by its adverse impacts. Therefore, it is crucial that the development of the sector not only shifts to the low-carbon path but also improves its resilience to climate change-related disruptions. This paper proposes a framework for an integrated analysis of electrification, climate change mitigation and climate change adaptation in the context of the Java-Bali power system in Indonesia. We have carried out analyses for the least-cost electrification and low-carbon paths. Our analyses reveal that the low-carbon path has benefits in term of reducing CO_2 emissions, but entails higher costs.

Furthermore, we have carried out an intensive fieldwork and identified the historical effects of severe weather and changes in climate variables on power plants. We have also developed scenarios of future climate change impacts that are relevant to the electricity sector. Our ongoing work attempts to parameterize the identified impacts of climate change into the changes in technical characteristics of TPPs and HEPPs. Subsequently, our future work will integrate those changes into analyses of long-term power system expansion to satisfy the triple objectives of electrification, climate change mitigation and climate change adaptation.

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