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Seeking for a climate change mitigation and adaptation nexus: Analysis of a long-term power system expansion

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HIGHLIGHTS

- Integrated analysis of climate change mitigation and adaptation in the power sector.
- Climate change constraints are incorporated into simulations of a power system expansion.
- The impacts of climate change on the electricity demand and supply are quantified.
- WEAP and LEAP software tools are used.
- Results indicate the nexus between climate change mitigation and adaptation.

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ABSTRACT

Reductions in carbon emissions have been a focus of the power sector. However, the sector itself is vulnerable to the impacts of global warming. Extreme weather events and gradual changes in climate variables can affect the reliability, cost, and environmental impacts of the energy supply. This paper analyzed the interplay between CO_2 mitigation attempts and adaptations to climate change in the power sector using the Long-range Energy Alternative Planning System (LEAP) model. This paper presented a novel methodology to integrate both CO_2 mitigation goals and the impacts of climate change into simulations of a power system expansion. The impacts on electricity supply and demand were quantified, based on historical climate-related impacts revealed during fieldwork and existing literature. The quantified effects, together with climate mitigation targets, were then integrated into the LEAP modeling architecture. The results showed a substantial alteration in technology composition and an increase in installed capacities driven by the joint climate mitigation–adaptation efforts when compared with the scenario without mitigation and adaptation (reference). Furthermore, an increase in CO_2 emissions was observed under the mitigation-adaptation scenario compared with the mitigation only scenario, indicating that the power sector's adaptations for climate change are likely to hinder CO_2 mitigation efforts. Therefore, a nexus between mitigation and adaptation should be exploited in the policy development for a low-carbon and climate-resilient power system.

1. Introduction

The energy sector contributes significantly to global warming. Accordingly, most of the Nationally Determined Contributions (NDCs) submitted by Parties to the United Nations Framework Convention on Climate Change (UNFCCC) included energy sector emission reduction components, as strategies for meeting their pledges under the Paris Agreement [1]. However, the energy sector is also vulnerable to the impacts of climate change (CC). Extreme weather events and gradual changes in climate variables can affect the reliability, cost, and environmental impacts of the energy supply [2,3]. Therefore, meeting climate mitigation goals while simultaneously coping with CC impacts represents a tremendous challenge for the energy sector. In developing countries, this challenge often coincides with vital electrification objectives, caused by rapid growth in electricity demand.

The societal challenge of transitioning from fossil fuels to renewable

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Nomenclature

Δ	slope vapor pressure curve
β	the power temperature coefficient
η_T	the temperature derating factor
γ	psychrometric constant
$C_p(T_{sw})$	condenser pressure at seawater temperatureT_{sw}
CF_{Tm}	annual capacity factor at temperatureT_m
$Dp(T_m)$	annual peak demand at temperatureT_m
e_a	actual vapor pressure
e_s	saturation vapor pressure
E_{Ref}	annual energy generation at referent temperature
ET	evapotranspiration
E_{Tm}	annual energy output
G	soil heat flux density
P	installed capacity
$P(T)$	power output at temperature$T$
R_n	net radiation at the crop surface
T_m	the mean air temperature
T_{Ref}	the referent temperature
T_{sw}	seawater temperature
u_2	wind speed

Abbreviation

EURO-CORDEX	European Coordinated Regional Downscaling Experiment
GEP	Generation Expansion Planning
HiREPS	High-Resolution Power System
LEAP	Long-range Energy Alternative Planning system
MAED	Model for Analysis of Energy Demand
MARKAL	MARket ALlocation
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
POLES	Prospective Outlook on Long-term Energy Systems
TIAM-ECN	TIMES Integrated Assessment Model of the Energy research Centre of the Netherlands
TIMES	The Integrated MARKAL/EFOM System
WEAP	Water Evaluation And Planning system

energy in response to the Paris Agreement triggered significant research efforts. Grande-Acosta and Islas-Samperio [4] provided alternative scenarios for decarbonizing the Mexican power sector, by assessing 36 mitigation options, using the Long-range Energy Alternative Planning System (LEAP). Handayani et al. [5] also employed LEAP to analyze scenarios that would allow the Indonesian power system to meet both electrification and CC mitigation goals. Dalla Longa and van der Zwaan [6] adopted the TIAM-ECN model to analyze the roles played by low carbon technologies in attempts to achieve the Paris Agreement climate targets in Kenya. A study of the Malaysian power sector, conducted by Haiges et al. [7], utilized the TIMES model to assess long-term power generation options while also considering CC mitigation. Guo et al. [8] analyzed the de-carbonization of the Chinese power sector using a multi-region dispatch model, revealing unintended consequences of the de-carbonization pathway, such as the disturbance in the stability and integrity due to intermittent renewable energy generation. Overall, these studies have indicated that the Paris Agreement targets are achievable but are also associated with various consequences, such as increasing costs and alterations in technology and energy mixes.

While mitigation efforts are vital, the adverse impacts of CC already affect various sectors of social-economic systems that may either facilitate or hinder the mitigation efforts made by the power sector [3]. Previous studies have paid little attention to adverse CC impacts that are expected to impact entire elements of the power system. Electricity supply and demand are the first factors likely to be affected. On the supply side, CC impacts include changes in water availability and the seasonality of hydropower, alterations in wind speed frequencies and distributions, reductions in solar cell efficiency, declines in generation cycle efficiencies and the availability of cooling water for thermal power plants, and the failures and capacity reductions of transmission and distribution lines. On the demand side, CC alters heating and cooling patterns [2,3,9]. Neglecting these impacts can undermine efforts to decarbonize the energy sector [3].

Furthermore, the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) has recognized that the CC impacts and adaptation responses of the energy system represent research gaps and urge the integration of these issues into assessments of climate stabilization pathways [10]. Because CC impacts could influence the effectiveness of mitigation options, the integration of these factors crucial when developing mitigation plans. AR5 also highlighted the scarcity of publications regarding CC impacts, adaptations, and vulnerability in developing countries [11]. This paper aimed to address these gaps in the literature by conducting a holistic analysis of low-carbon pathways for the power sector while accounting for adverse CC impacts. Both CC mitigation goals and CC impacts were integrated into modeling simulations of power system expansions, using the primary power system of Indonesia, Java-Bali, as a case study. Indonesia is an emerging and developing economy, with fast-rising electricity demand, and aims to develop a low-carbon energy system, targeting a 23% share of renewable energy in the national energy mix, by 2030, and a 31% by 2050. These targets are in line with the country's NDC, which pledge to reduce CO_2 emissions by 29%.

LEAP was used to conduct long-term expansion simulations for the Java-Bali power system. The modeling tool was chosen over 30 models potentially suitable for the analysis of this paper, owing to its ability to accommodate the technological complexity of the power system, its support for alternative scenario projections, its least-cost optimization modeling of power system expansions, and its ability to calculate CO_2 emissions from various power generation technologies. Furthermore, LEAP is freely accessible to students and academia in developing countries and has user-friendly features. The models' screening procedure and the validation of the Indonesian LEAP model were reported in our previous work [5].

Prior to commencing the simulations, the impacts of CC on electricity demand and supply were quantified based on intensive fieldwork performed in Indonesia - which revealed the past impacts of climate-related events - and secondary data from the literature. The quantified effects, together with the renewable energy targets, were then converted into constraints on the technological characteristics of power plants, within the LEAP optimization modeling architecture.

The paper offers two innovative contributions to the academic literature and real-world practices. First, to the best of our knowledge, this research is the first attempt to jointly consider CC mitigation goals and CC impacts on various types of power generation technologies and electricity demand, while modeling power system expansions using LEAP. An explicit link between the sectoral efforts to pursue a low-carbon pathway and its adaption to adverse CC impacts requires novel methodological development. This article makes steps in filling this important gap in the literature by outlining the methodology and illustrating its feasibility in a case study. Second, this paper adds to the scarce literature regarding the impacts of CC, particularly the vulnerability and adaptation of the power sector in developing countries, by quantifying sector-wise costs of CC. As such, it may serve as a reference for the development of policies that facilitate the formation of a low-carbon and climate-resilient power sector.

The remaining portions of this paper proceed as follows. Section 2 describes the existing literature regarding power system expansion modeling under CC conditions and outlines the existing knowledge gaps. Section 3 describes the employed methodology, and Section 4 describes the LEAP modeling results for each scenario. Section 5 discusses the significance of these findings. Finally, Section 6 provides conclusions, discusses the limitations of this study, and makes recommendations for future work.

2. Modeling climate change impacts on the power sector

Increasingly, the idea that the electricity sector is vulnerable to the effects of CC being recognized, as is the need to quantify these impacts using models. Tobin et al. [12] investigated the impacts of CC on four electricity supply technologies (wind, solar photovoltaic [PV], hydro, and thermal power) in 28 European Union (EU) countries, based on the European Coordinated Regional Downscaling Experiment (EURO-CORDEX) regional climate model projections. Other studies have focused primarily on the impacts of CC for thermoelectric power plants. Kern and Characklis [13] used a systemic framework to assess the impacts of CC-associated drought on the financial exposure of a major utility in the Southeastern part of the United States (U.S.). Cook et al. [14] developed a methodology for predicting the risk that power plants will violate thermal pollution limits, due to climate-induced drought and heatwaves in the Upper Mississippi River Basin and Texas. Furthermore, van Vliet et al. [15] analyzed the impacts of CC-associated changes in temperature and water availability 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. [16] investigated the vulnerability of Chinese thermoelectric power plants to water scarcity problems, by performing a high-resolution evaluation and projection of spatial vulnerability. Collectively, these studies agreed that the adverse effects associated with changes in climate variables, such as temperature, and precipitation, would likely reduce the power generation capacities of thermoelectric power plants.

Adverse impacts associated with gradual changes in climate variables on wind and solar PV have been found to be limited [12,17,18]. Moreover, Lucena et al. [18] and Pašičko et al. [19] estimated increased wind power production under future climate conditions in some parts of Brazil and Croatia, respectively. However, off-shore wind power plants may require investments for adaptation measures that counteract rises in the sea level [20].

The results regarding CC impacts on hydropower have been mixed. Anugrah et al. [21] evaluated the Bayang micro hydropower system in Indonesia, using the Water Evaluation And Planning System (WEAP)-LEAP models, and found that CC will reduce power production. Guerra et al. [22] employed a two-stage stochastic approach to power system design and planning to analyze the impacts of CC on the hydro-dominant Columbian power system, which suggested that CC will reduce the capacity factor of hydropower plants in Columbia. Meanwhile, Boehlert et al. [23] evaluated the impacts of CC on hydropower generation in the U.S., using a set of linked models, which suggested a possible increase in future hydropower generation due to increased river runoff, based on high-emission scenarios in the Pacific Northwest.

Compared with other energy sources, the potential CC impacts on hydropower have been extensively incorporated into simulations of long-term power system expansion. This high level of attention is likely due to the hydropower dominance of the energy sector in some countries, the long asset lifetime associated with hydropower, and the apparent dependence of hydropower on climate-related factors [3]. Integrating potential CC impacts into simulations of power system expansions allows the associated impacts of CC to be analyzed for the entire power system. The studies that have examined CC impacts include Lucena et al. [24], for the Brazilian power sector, Teotónio et al. [25], for the Portuguese power system, Arango-Aramburo et al. [26], for the Colombian power sector, and Spalding-Fecher [27], for the Southern African Power Pool. Overall, these studies have indicated a decline in hydropower generation under CC conditions, although differences exist in the degree of decline, depending on the country of interest. Consequently, extra capacity from other energy sources may be required to compensate for a future lack of hydropower reliability.

On the demand side, previous studies have often indicated increases in electricity consumption capacity associated with CC, such as in the U.S. [28,29,30], the Southeastern Mediterranean region [31], Brazil [24], and Hong Kong [32]. A net increase in demand has also been indicated in Austria and Germany [33]. In contrast, the total energy demand of the EU is expected to decrease [34]. Similarly, a study examining Norway [35] also suggested a net decrease in energy demand.

Several studies have integrated multiple CC-associated impacts on energy demand and various types of energy production technologies into simulations of long-term power system expansions, allowing their combined effects on the system to be examined. Lucena et al. [24] incorporated expected CC-associated impacts on electricity demand, hydropower capacity, and natural gas turbine capacity into simulations of the long-term expansion of the Brazilian power sector, using Model for Analysis of Energy Demand (MAED)-Model for Energy Supply Strategy Alternatives and their General Environmental Impact (MESSAGE) models. Seljom et al. [35] employed market allocation (MARKAL) modeling to integrate CC-associated impacts on hydro and wind power, as well as energy demand, into an analysis examining the future of the Norwegian energy system. Meanwhile, Dowling [34] analyzed the European energy system, considering CC-associated impacts on energy demand and various types of power production methods, including thermoelectric, wind, solar PV, and hydroelectric power generation, by utilizing the Prospective Outlook on Long-term Energy Systems (POLES) model. A similar study examining Europe was conducted by Mima and Criqui [36], with a smaller scope, including only energy demand, thermal power plants, and hydropower. Totschnig et al. [33] employed the High-Resolution Power System (HiREPS) to integrate the impacts of CC and fuel price changes on energy demand and various types of energy production methods into simulations of future Austrian and German power sectors. Finally, Li et al. [37] incorporated the effects of projected changes in temperature, precipitation, and extreme events on electricity demand and various power supply types into simulations of power system expansion for several U.S. regions, using a robust electric power Generation Expansion Planning (GEP) optimization model. These studies have all agreed that the reliability of thermal power plants will decrease under CC conditions. Meanwhile, the CC impacts on solar PV and wind have been estimated to be minor [35,34]. The results for Norway have revealed lower estimated system costs due to a projected net decrease in demand. Furthermore, Norway is likely to benefit from an increase in hydropower production. In contrast, Brazil is likely to suffer from reduced hydropower reliability, requiring extra installed capacity, and, consequently, requiring extra investment costs.

However, to the best of our knowledge, research explicitly linking the impacts of CC with the energy sector's climate mitigation goals remains lacking. Hence, how CC impacts may interfere with the power sector's efforts to achieve national long-term climate mitigation goals remains unexplored. An integrated assessment of CC mitigation and adaptation in the power sector is especially vital for developing countries, which already face adverse CC impacts and rising electrification demands, on top of CC mitigation goals. This paper addressed this important gap by pursuing a comprehensive assessment of the nexus between electrification, CC mitigation, and CC adaptation in developing countries, using Indonesia as an example.

3. Methodology and data

This study simulated the future development of the Indonesian power system, taking into consideration both CC mitigation and adaptation. This study focused particularly on the extensive Java-Bali power system, which provides 75% of total Indonesian electricity consumption [38], serves 59% of the Indonesian population [39], and mirrors the national power sector in terms of the historical energy mix, supply, and demand [40].

To account for CC mitigation, a long-term scenario for Java-Bali power system expansion was developed that included the country's low-carbon development policy (Fig. 1, left side of the flow chart). Subsequently, LEAP, an energy system model developed by the Stockholm Environment Institute (SEI), was used to analyze the low-carbon pathway. LEAP is a prominent model that has been used in 190 countries [41], 85 UNFCCC country reports [42], and more than 70 peer-reviewed journal papers [43]. The popularity of LEAP makes results using this model comparable across countries, which is especially relevant when major international agreements, such as the Paris accord, are considered. As a bottom-up energy model, LEAP offers the capability to analyze both power system expansion and climate policy scenarios, taking into account the detailed characteristics of electric power technologies. A detailed description of LEAP is provided in Appendix A.

For the adaptation[1] component, a 3-step approach was applied (Fig. 1, right side of the flow chart). First, data were collected regarding the historical impacts of severe weather events and gradual changes in climate variables on the power sector, through semi-structured interviews and focus group discussions at 10 major power plants, between February and March 2018. The fieldwork revealed that weather and climate affect all segments of the power system, which include generation, transmission, and distribution. Greater details regarding the findings from the fieldwork were presented in Handayani et al. [44]. Second, a literature review examining CC scenarios was performed to identify likely trends in temperature, precipitation, and sea surface temperatures for the Indonesian archipelago. Finally, the variables and functions necessary for the LEAP model architecture were identified to parameterize the projected impacts of CC on the Java-Bali power system.

The impacts of CC were considered in terms of both demand and supply. To consider the impacts of CC on energy demand, this paper estimated how gradual changes in temperature might affect the electricity requirements of the Java-Bali system. Although the fieldwork revealed that extreme weather events, such as heatwaves, have caused the temporary shutdown of several power plants [44], this paper excluded extreme weather events from the simulation model, due to methodological and data-associated limitations; therefore, the inclusion of these extreme weather events will be an important direction for future work.

To consider the impacts of CC on energy supply, the impacts of CC on power generation were quantified, focusing on four power plant types: coal-fired power plants (CFPPs), natural gas power plants (NGPPs), hydroelectric power plants (HEPPs), and solar photovoltaic (solar PV) power plants. CFPPs, NGPPs, and HEPPs were chosen because they constitute most of Indonesia's power generation capacity, at 50%, 28%, and 9%, respectively. Solar PV was included because this type of power generation is expected to play a significant role in Indonesia's transition to a low-carbon energy system [40]. The impacts of CC on wind power have been discussed in the literature. For example, Schaeffer et al. (2012) indicated that alterations in wind speed may influence the ability to optimize a wind energy source with a wind turbine power curve [2]. Further modeling studies may quantify these impacts and integrate them into LEAP simulations for power system expansions, enabling a more comprehensive analysis of the impacts of CC on the power system.

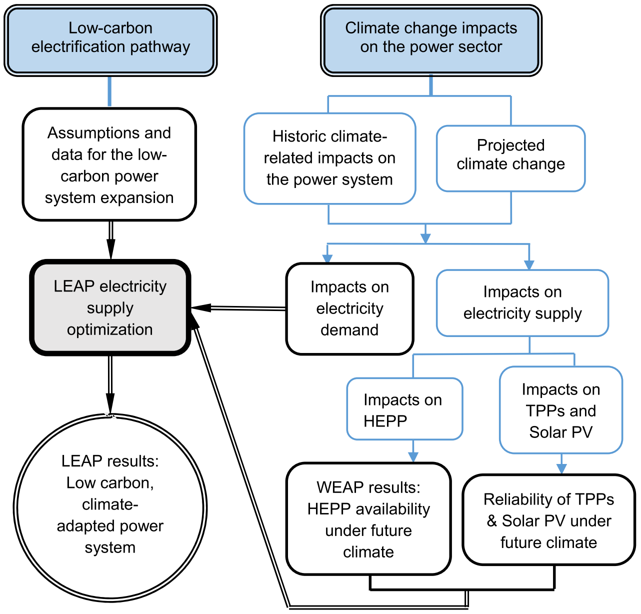

Fig. 1. The conceptual framework for integrating climate change mitigation and adaptation, using WEAP-LEAP models.

This paper focused on the analysis of how gradual changes in climate variables, including surface air temperatures, precipitation levels, and sea surface temperatures, impact the power system. WEAP was employed to analyze how changes in precipitation and temperature may impact water availability for hydroelectric power plants. In addition, this present paper relied on the findings from fieldwork and from the current literature to parameterize the expected CC impacts on thermal power plants (TPPs) and solar PV.

Finally, LEAP was used to simulate the Java-Bali power system expansion, while considering the national low-carbon policy targets and the CC impacts on the power system. These simulations quantified the electricity mix and corresponding costs of climate-resilient energy systems while ensuring that the electrification, CC mitigation, and adaptation goals are being met.

3.1. Scenario development

3.1.1. Climate change scenarios

The CC projections in this study are based on the Representative Concentration Pathway (RCP) 4.5 and RCP8.5 scenarios that were adopted in the IPCC AR5. RCP4.5 is a medium-stabilization scenario that assumes a stable radiation intensity, at approximately 4.5 W/m^2 or equivalent to 650 ppm CO_2 eq., after 2100. RCP8.5 a very-high-baseline emission scenario, which assumes a constant increase in pathways leading to 8.5 W/m^2 of radiation intensity (more than 1,370 ppm CO2 eq.), in 2100 [45]. The CC projections for Indonesia in this study included these scenarios. The projections for temperature and precipitation (Table B.1. Appendix B) were based on the ensemble values from 35 Coupled Model Intercomparison Project (CMIP) models, which are available at the World Bank Climate Knowledge Portal website [46] and were derived from those used by Harris et al. [47]. These data are available for two periods within our study's time horizon: 2020–2039 and 2040–2059. Meanwhile, the projected sea surface temperature data were obtained from the output of a global climate model from the Institut Pierre Simon Laplace, which was retrieved from the International Pacific Research Center website[2] [48]. Based on these data, the effects of climate-related variables on electricity demand and the key technical characteristics of various power plants were quantified.

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[1] Adaptation is defined here as variations in the power system configuration (e.g., installed capacity, technology composition), due to the CC-induced reductions in power supply reliability and changes in electricity demands.

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

3.1.2. Power system expansion scenarios

The three following scenarios for the expansion of the Java-Bali power system were developed for the period from 2018 to 2050.

Reference scenario (REF): a power system expansion scenario, without CC considerations. The objective of this scenario is to satisfy the growing future demand for electricity in the Java-Bali islands at the lowest overall cost.

CC mitigation scenario (CCM): this power system expansion scenario assumes a shift to a low carbon pathway, based on Indonesia's New and Renewable Energy (NRE) targets, increasing the share of renewable energy to 23%, by 2025, and 31%, by 2050. In addition to these mitigation targets, this scenario includes electrification targets but neglects adaptations to CC.

CC mitigation and adaptation scenario (CCMA): this power system expansion scenario assumes a shift to a low-carbon pathway and integrates the effects of projected CC on both electricity supply and demand. Based on the CC scenarios discussed in Section 3.1.1, two CCMA scenarios were examined:

a. CCMA RCP4.5: CC impacts on power plants were quantified based on the IPCC RCP4.5 scenario
b. CCMA RCP8.5: CC impacts on power plants were quantified based on the IPCC RCP8.5 scenario

The Java-Bali LEAP model is described in detail in Handayani et al. [40]. In addition to the methodological advances associated with the inclusion of the CCMA scenarios, this present study updates the previous study by including the most recently available historical data regarding energy demand and supply. Accordingly, the LEAP base year has been updated from 2015 to 2017. Furthermore, the electricity demand projection was updated based on the most recently available electricity supply business plan (RUPTL 2018–2027) [49]. Likewise, the capital costs of electric power technologies have now been assumed to decrease every five years, based on the percentage of technology cost reductions reported by the World Energy Outlook [50]. Table 1 and Table 2 list the primary assumptions made for the Java-Bali LEAP model. Meanwhile, the potential renewable energy sources that were exploited by this modeling simulation are presented in Table C.1. Appendix C.

3.2. Integrating adverse CC impacts into the LEAP model

3.2.1. Demand-side

3.2.1.1. Projecting the impacts of higher temperatures on electricity demand. Prior to estimating future climate-driven electricity demands, the actual hourly load data and the peak electricity demand data were collected from the Java-Bali Load Control Center. Comparing these data to temperature data collected from 23 weather stations, retrieved from the Agency for Meteorology, Climatology, and Geophysics [61], demonstrated a significant correlation between temperature and electricity demand [44]. A first-order estimate was performed to determine the effects of projected higher temperatures on annual peak demand, using Eq. (1).

$$Dp(T_m) = 521.55T_m + 5788.3 \tag{1}$$

where $Dp(T)$ is the annual peak demand (in MW) and T_m is the mean air temperature (°C).

The results showed that the annual demand for electricity is likely to increase by 1.2% and 1.4% by 2020, under the CCMA RCP4.5 and CCMA RCP8.5 scenarios, respectively, compared with the REF scenario. Furthermore, by 2040, electricity demand is likely to increase by 2% and 2.8%, respectively.

3.2.2. Supply-side

As a bottom-up energy model, LEAP allows the detailed characteristics of energy technologies to be determined as input data; therefore, the technical characteristics of a power plant can be altered to integrate the effects of CC. Based on data gathered through fieldwork and from the literature that has reported the impacts of weather and climate on power plants' performances, these effects could be quantified. The most detrimental effects, such as changes in surface air temperature and precipitation, were identified and transformed into changes in the technical characteristics of power plants. The altered technical characteristics included capacity factors and efficiency. These changes were expected to influence the technology mix and installed capacities and to reflect the costs of the power system adapting to CC.

3.2.2.1. Projecting the impacts of temperature and precipitation changes on HEPPs. In this study, WEAP was employed to simulate future hydrology in the Citarum river basin, based on projected changes in air temperatures and precipitation. The Citarum river provides water for the two largest HEPPs in Indonesia, Saguling and Cirata, with installed capacities of 1008 MW and 797 MW, respectively (see Fig. D.1., Appendix D). WEAP is commonly used to simulate water demand, supply, flow, storage, discharge, and pollution scenarios. Therefore, this method is suitable for analyzing water availability for HEPPS under future CC scenarios. Furthermore, WEAP has a built-in link to LEAP modeling, where the hydropower availability modeled by WEAP becomes an input for LEAP. Hence, the use of both software tools together enables the dynamic analyses of CC implications for hydropower production [62].

Temperature can affect water availability in a watershed system. Higher temperatures result in larger amounts of surface water being returned to the atmosphere, through evaporation and transpiration, also known as evapotranspiration. In WEAP, evapotranspiration is calculated using the following U.S. Food and Agricultural Organization (FAO) Penman-Monteith equation, as outlined in the FAO Irrigation and Drainage Paper No. 56 [63].

$$ET = \frac{0,408\Delta(R_n - G) + \gamma\frac{900}{T+273}u_2(e_s - e_a)}{\Delta + \gamma(1 + 0,34u_2)} \tag{2}$$

where ET is the evapotranspiration rate (mm/day), R_n is the net

Table 1
Summary of the model input parameters.

Input Data	Value	Source
Annual demand growth 2016–2030	4–6%	Refers to the RUPTL and IEO estimates [51,49]
Transmission & distribution losses	7.9–8.5%	Refers to the draft RUKN estimates [52]
Reserve margin*	35%	Refers to the RUKN criteria [52]
Environmental parameter	Per technology	The IPCC Tier 1 default emission factors, embedded in the LEAP's technology database [41]
Discount rate	12%	The discount rate used by PLN [53]

Notes: IEO = Indonesia Energy Outlook, RUKN = Rencana Umum Ketenagalistrikan Nasional (National Electricity General Plan), PLN = Perusahaan Listrik Negara (State Electricity Company)

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

Table 2
Characteristics of the energy technologies included in the Java-Bali LEAP model.

Technology	Lifetime of power plant (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 $/MWh)[a]	Fuel cost[c] (2015 US$)
Ultra-supercritical coal	30	40	80	100	1400	31.3	2	51.8 US$/ton
Natural gas combined cycle	25	55	80	100	800	19.2	1	7.6 US $/MMBTU
Natural gas open cycle	20	36	80	100	700	18	1	7.6 US $/MMBTU
Hydro	50	100	41	51	2000	6.6	1	–
Mini hydro	25	100	46	58	2400	6.6	1	–
Hydro-pumped storage	50	76	20	25	800	6.6	1	–
Geothermal	25	10[d]	80	100	3500	30	1	–
Solar PV	20	100	17	22	2069[e]	24.8[e]	0.4[b]	–
Wind power	20	100	28	35	2200	44[d]	0.8[b]	–
Nuclear	40[f]	34	85[g]	100	6000	164[d]	8.6[g]	9.33 US$/MWh[f]
Biomass	20[h]	35[d]	80	100	2228[d]	78[d]	6.5[b]	11.67 US$/ton[h]

* Efficiency is defined as the percentage ratio of energy outputs to feedstock energy inputs in each process.

** Maximum availability in LEAP is defined as the ratio of the maximum energy produced to the potential production if the process ran at full capacity for a given period (expressed as a percentage). The 'maximum availability' data, together with the installed capacity data for a power plant, determine the annual electricity production of the power plant [41].

*** Capacity credit in LEAP is defined as the fraction of the rated capacity considered firm for calculating the reserve margin. The values are calculated based on the ratio of availability for the intermittent plant to the availability for a standard thermal plant [41].

**** OM: Operation and Maintenance. Sources:

[a] PLN[54].

[b] DEN [55].

[c] PLN [56].

[d] OECD/IEA [50].

[e] ACE [57].

[f] Rothwell & Rust [58].

[g] IEA & NEA [59].

[h] IRENA [60].

radiation at the crop surface level (MJ/m^2/day), G is the soil heat flux density (MJ/m^2/day), T is the mean air temperature (°C), u_2 is the wind speed (m/s), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), Δ is the slope vapor pressure curve (kPa/°C), and γ is the psychrometric constant (kPa/°C). Detailed descriptions of the WEAP methodology are provided in Sieber [64] and Yates et al. [65]. The WEAP input data used for the HEPPs simulations in this study can be found in Table D.1, Appendix D.

The results showed that under the CCMA RCP4.5 scenario, the average annual capacity factors for both the Saguling and Cirata HEPPs varied across years when compared with the REF scenario (Fig. D.2., Appendix D). Under the CCMA RCP4.5 scenario, both Saguling and Cirata were projected to produce slightly less electricity ($< 1\%$) than under the REF scenario from 2022 to 2039. In contrast, their electricity production increases relative to the REF scenario starting in 2040, resulting in the aggregate HEPP production over the study period being higher under the CCMA RCP4.5 scenario than under the REF scenario. No significant difference in the annual average capacity factor over time was observed between the REF and RCP8.5 scenarios. In addition, the aggregate HEPP production for the RCP8.5 scenario was slightly lower than that for the REF scenario. These results were extrapolated to the remaining HEPPs when simulating the Java-Bali power system expansion using the LEAP-WEAP combination.

3.2.2.2. Sea surface water temperatures and the efficiencies of CFPPs. A cooling water system is an essential component of CFPPs. CFPPs in the Java-Bali power system rely on seawater for their cooling systems and are likely to be impacted by the higher seawater temperatures expected under CC conditions. The CFPPs in Indonesia employ once-through cooling systems, which circulate seawater through pipes to absorb heat from steam in condensers. The warmer water is then discharged back to the sea. A higher cooling water temperature results in increased condenser pressures, which reduces the energy efficiency of the condenser [66]. Based on data from the Paiton PJB CFPP, which is a typical CFPP that uses a once-through cooling system, the relationship described by Eq. (3), between cooling water temperature and the performance of a condenser vacuum, was identified [44].

$$C_p(T_{sw}) = -3.4339T_{sw} + 796.33 \tag{3}$$

where $C_p(T_{sw})$ is the condenser pressure (mmHg) and T_{sw} is the seawater temperature (°C).

Furthermore, this relationship was combined with data regarding the primary energy consumption of the power plant, revealing that for every 1 °C increase in the cooling water temperature above 25 °C, the power plant efficiency drops by 0.32%. This relationship was used to estimate changes in CFPP efficiencies following the anticipated CC-associated changes in the surface seawater temperatures. The results showed that reductions in the efficiencies of Java-Bali CFPPs are expected to range from 0.1% to 0.4%, under the RCP4.5 scenario, and from 0.03% to 0.3%, under the RCP8.5 scenario. These drops in efficiency are expected to increase fuel consumption, leading to increased fuel costs and CO$_2$ emissions.

3.2.2.3. Precipitation and capacity factors for CFPPs. Our fieldwork revealed that heavy precipitation dampens coal stored in open storage areas, reducing the burning efficiency of CFPPs [44]. Damp coal is a particular issue during the wet season when precipitation is intense and frequent. Suralaya CFPP, the largest CFPP in Indonesia, provided operation disruption data from 2011 to 2017, which included past disruptions caused by wet coals. Based on these data, average annual reductions in CFPP capacities were calculated, based on reductions in energy generation that were attributable to wet coals.

Furthermore, historical data regarding CFPP disruptions and local precipitation were combined with projected precipitation estimates under CC conditions to estimate the expected reductions in CFPP capacities due to future precipitation events. The results indicated that the CFPP capacity factor will be reduced by 0.29% and 0.30%, respectively, by 2020 and 2040. These estimates were adopted in the LEAP simulations for the remaining Java- Bali CFPPs.

3.2.2.4. Ambient air temperatures and power outputs of NGPPs. Two types of NGPP technologies are utilized in the Java-Bali power system: open cycle gas turbine (OCGT), which produces electricity solely from a gas combustion turbine, and combined cycle gas turbine (CCGT), which produces electricity from the gas combustion turbine and generates extra electricity by routing waste heat from the gas turbine to a nearby steam turbine. High ambient air temperatures primarily affect the operation of NGPP gas turbines because gas turbine operation intakes ambient air for the compressor and routes the air into the burning chamber. Higher ambient air temperatures reduce the air density, which, in turn, reduces the burning efficiency and power outputs [67]. According to the field data collected from Muara Karang NGPP, every 1 °C increase in ambient air temperature above 16 °C reduces the power output of the OCGT by 0.6%. Accordingly, the power output of the Muara Karang OCGT correlates with air ambient temperatures, as described by Eq. (4). These data are comparable with previously reported findings in the literature, which indicated that each 1 °C increase in temperature above 30 °C reduced gas turbine power outputs by 0.50–1.02% [68,69,70]. Furthermore, the literature indicated that the overall net reduction in CCGT power outputs ranges from 0.3% to 0.6%. Here, the power outputs of CCGTs were assumed to drop by 0.45%, which is the middle value of the range. Accordingly, the power output of CCGTs correlated with ambient air temperatures as described by Eq. (5).

Furthermore, the monthly energy outputs of OCGTs and CCGTs were estimated under CC scenarios based on average monthly temperature projections, using Eq. (4) and Eq. (5), respectively. The annual capacities for NGPPs under CC scenarios were calculated using Eq. (6). The results showed that the expected reductions in the capacities of the Java-Bali NGPPs by 2040 ranged from 0.8% to 4.3%.

$$P(T) = P * (-0.006T + 1.0933) \tag{4}$$

$$P(T) = P * (-0.0043T + 1.0662) \tag{5}$$

$$CF_{Tm} = \frac{E_{Tm}}{Plantcapacity(MW) * 8760hours} \tag{6}$$

where $P(T)$ is the power output, at temperature T (MW), P is the installed capacity (MW), E_{Tm} is the annual energy output (MWh), T_m is the mean air temperature (°C), and CF_{Tm} is the capacity factor.

3.2.2.5. Air temperatures and solar PV efficiencies. Increased air temperature may negatively affect the performance of solar PVs, manifested as a decrease in the PV efficiency, determined by the temperature coefficient, which is a correction factor for efficiency as a function of temperature [71]. The estimate reported by Pašičko et al. [19] was utilized, in which every 1 °C increase in air temperature decreases the PV efficiency by 0.5%, relative to the referent value at 25 °C. This value is consistent with the average temperature coefficient specified by Dubey et al. [72]. Based on this assumption, the temperature derating factor of the Java-Bali solar PV caused by CC-associated temperature increases can be estimated using Eq. (7)[3], and subsequent reductions in the annual power generation by solar PV can be calculated using Eq. (8).

$$\eta_T = 1 - [\beta(T_m - T_{Ref})] \tag{7}$$

$$E_{T_m} = \eta_T x E_{Ref} \tag{8}$$

where η_T is the temperature derating factor, β is the power temperature coefficient, Tm is the mean air temperature (°C), T_{Ref} is the referent temperature, E_{T_m} is the annual energy generation (MWh) and E_{Ref} is the annual energy generation at referent temperature (MWh).

The results indicated that the derating of solar PV outputs under future expected air temperatures will result in solar PV capacity being reduced by 0.5% to 0.6%, during the 2020 s, and by 0.8% to 1.1%, during the 2040 s.

4. Climate change mitigation-adaptation synergies: LEAP results

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

4.1. Installed capacity and electricity mix

4.1.1. Reference scenario

Under the REF scenario, which assumes the least-cost electrification pathway, without considering CC mitigation and adaptation strategies, the capacity of fossil fuel technologies increases rapidly. The coal and natural gas capacities reach 115 GW and 53 GW, by 2050, respectively, which represent six-fold and five-fold increases, respectively, compared with their capacities in 2017. As a result, the capacity mix during the study period becomes heavily fossil fuel-dependent (Fig. 2a). In 2050, coal maintains its dominance under the REF scenario (Fig. 2b), comprising 72.4% of the Java-Bali electricity mix, followed by natural gas (20.7%), hydro (3.8%), and geothermal (3%) production.

4.1.2. Climate change mitigation scenario

The results showed that the implementation of the NRE policy (CC mitigation targets, as assumed by the CCM scenario) is likely to dramatically alter the Java-Bali capacity mix. In 2050, the coal capacity under the CCM scenario is expected to reduce by 41% compared with the REF scenario. These reductions in coal capacity are likely to be compensated by increases in the capacities 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 C.1, Appendix C) will be utilized, leaving wind and solar as the only potentially available renewable energy sources.

Accordingly, under the CCM scenario, the Java-Bali electricity mix is expected to mimic the changes in its capacity mix. Although fossil fuels supply most of the demand for electricity in the base year, their share is gradually reduced over time. Complying with the NEP-RE target, by 2025, renewables compose 23% of the electricity mix, shared among geothermal (9.6%), hydro (5.6%), biomass (6.5%), wind (1%), and solar (0.3%) (Fig. 3), Furthermore, by 2050, the renewable share increases to 31%, as targeted by the NRE policy. Interestingly, the electricity production from solar is expected to encompass 17.4% of the total electricity mix in 2050, the highest among all renewable energy sources, due to the relatively faster reductions expected for solar investment costs.

4.1.3. Climate change mitigation and adaptation scenarios

When the impacts of global CC are integrated on top of the CCM and electrification assumptions, the results depict the optimal choice for shifting the Java-Bali power system to a low-carbon pathway while also responding to the effects of CC. The results showed that extra capacities are necessary to serve climate-induced electricity demand surges and to cope with decreased power-generating capacities (Fig. 4). Under CCMA RCP4.5, the extra capacities of solar PV, coal, wind, and biomass relative to CCM are 7.5%, 5.4%, 19.9%, and 0.7%, respectively. In contrast, the natural gas capacity reduces by 2.2% compared with CCM. Naturally, the capacities of solar PV, coal, wind, and biomass increase to balance the growth in energy demand and to compensate for CC-induced declines in the power-generating capacities.

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[3] Other parameters (e.g., wind speed, solar radiation) were assumed to remain unchanged.

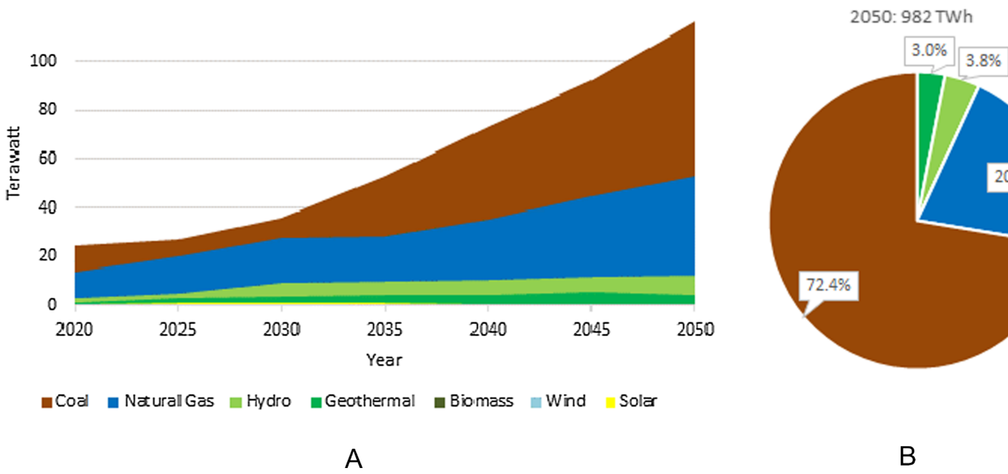

Fig. 2. Capacity mix over the study period for the reference scenario (a) and the electricity mix in 2050 (b).

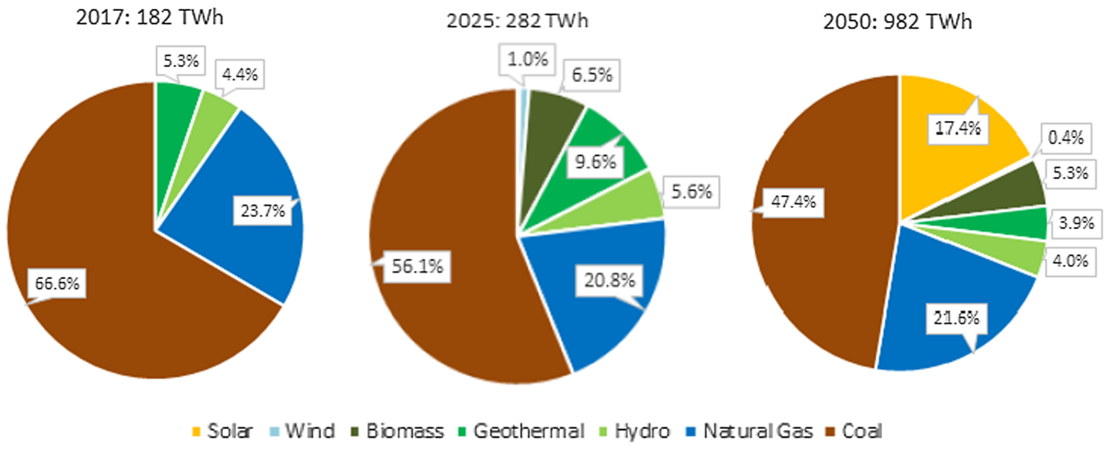

Fig. 3. The Java-Bali electricity mixes for 2017, 2025, and 2050, under the climate change mitigation scenario (CCM).

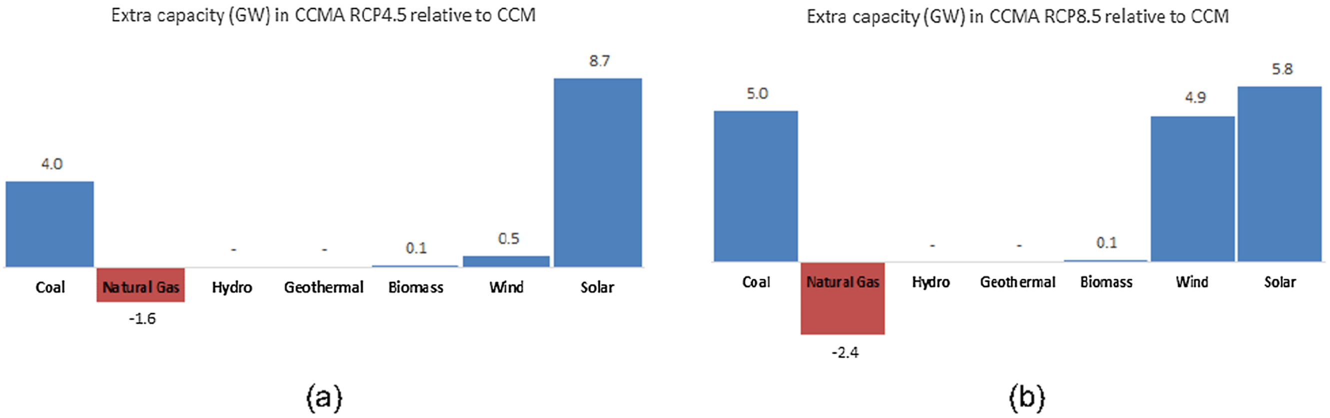

Fig. 4. Extra capacity under CCMA RCP4.5 (a) and CCMA RCP8.5 (b) conditions, using the CCM scenario as a benchmark.

Under CCMA RCP8.5, the extra installed capacity is even higher than observed under CCMA RCP4.5, indicating that the higher temperature scenario intensifies the impacts on both electricity demand and power supply (e.g., coal, natural gas, and solar PV). The extra capacity under CCMA RCP8.5 is expected to be shared almost evenly among solar, coal, and wind (Fig. 4.b). The increased penetration of wind power indicates a trade-off between CC mitigation and adaptation. First, wind resources potentially remain available to facilitate meeting NRE targets, whereas the extra capacity of coal is constrained by the NRE target. Second, because our simulation excludes the impacts of CC on wind power, under the higher temperature scenario (CCMA RCP8.5), wind power becomes more competitive, replacing a portion of the capacity provided by solar PV under other scenarios. However, the role of solar PV remains significant when anticipating climate-induced surges in demand, adding 5% more capacity than observed for the CCM scenario.

The extra installed capacity necessary to anticipate CC adds 299 TWh and 388 TWh of electrical energy, respectively, under the CCMA RCP4.5 and CCMA RCP8.5 scenarios between 2020 and 2050. Under the CCMA RCP4.5 scenario, the additional energy is primarily provided

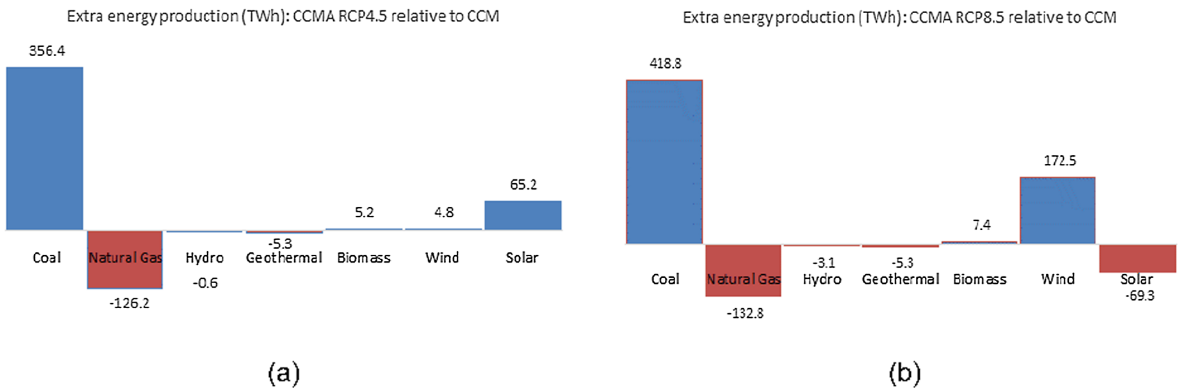

Fig. 5. Extra electricity production under CCMA RCP4.5 (a) and CCMA RCP8.5 (b) scenarios, using the CCM scenario as a benchmark.

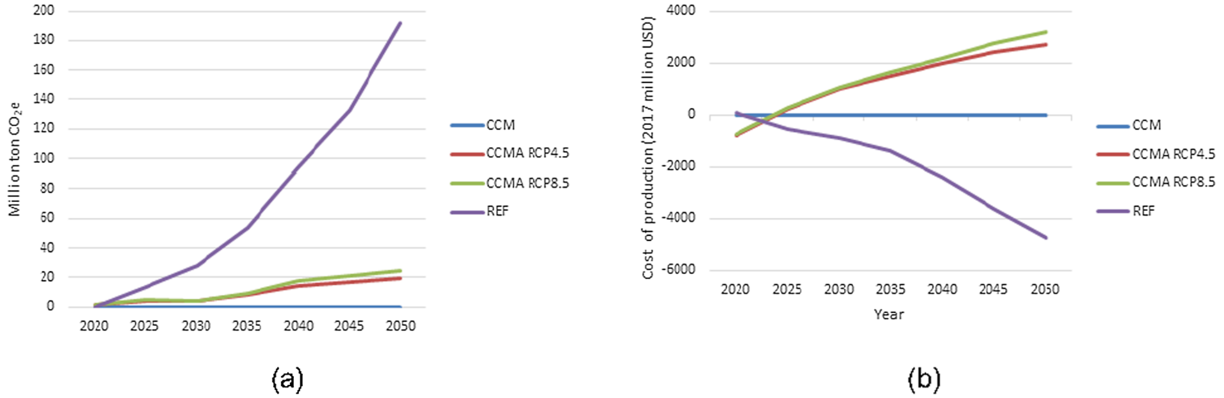

Fig. 6. CO_2 emissions (a) and total production costs (b) under reference, mitigation, and adaption scenarios. The CCM scenario is used as a benchmark.

by coal and solar PV (Fig. 5.a). Although solar PV adds an extra capacity under the CCMA RCP8.5 scenario (Fig. 4.b), it produces 6% less energy than under the CCM scenario, likely due to reductions in its efficiency, which is compensated by a significant increase in wind power production (Fig. 5.b).

4.2. CO_2 emissions and total costs

4.2.1. CO_2 emissions

Indonesia's NDC outlines the country's target of reducing 29% of its emission from business as usual (BAU) by 2030, and the energy sector is targeted to contribute 19% of the targeted CO_2 reductions. These simulation results revealed that under the REF scenario, the Java-Bali power system will emit 215 million tonnes of CO_2 in 2030 (Fig. 6.a). Meanwhile, under the CCM scenario, the CO_2 emissions are expected to decrease to 188 million tonnes, which represents a 13% reduction compared with the REF scenario. Therefore, additional efforts beyond the implementation of the NRE policy target are necessary to achieve the power sector's NDC target by 2030. By 2050, however, the CO_2 emissions are expected to drop further, to 34% lower than the REF scenario. Therefore, when the NRE target for 2050 has been fulfilled, Indonesia will be able to reduce its emissions beyond its current NDC targets.

When compared with the CCM scenario, the CO_2 emissions are expected to increase for both CCMA scenarios, with 20 and 25 million tonnes CO_2 expected for CCMA RCP4.5 and RCP8.5, respectively (Fig. 6.a). The additional CO_2 emissions are attributable to the expected increase in electricity production from coal, which is necessary to compensate for the climate-induced surge in electricity demand. Moreover, CFPP efficiencies drop under CC conditions, requiring additional coal consumption per unit energy produced. However, even with this increase, the CO_2 emissions are still expected to decrease by 30% compared with the REF scenario in 2050.

4.2.2. Total costs

Total costs were calculated based on the net present value of the total costs over the entire study period, which included capital costs, operation, and maintenance costs, and fuel costs. Under the REF scenario, the total costs of electricity production over the study period, from 2018 to 2050, are expected to reach 70.4 billion USD, which is equal to 0.1% of the cumulative national GDP during the study period[4].

Under the CCM scenario, the total costs of expanding the Java-Bali power system from 2018 to 2050 are expected to reach 75.1 billion USD. Therefore, shifting from the current regime to the low-carbon pathway is expected to add 4.7 billion USD to cost projections for the REF scenario, resulting in 6.8% higher costs compared with the REF scenario. Furthermore, when CC impacts are considered, the costs grow by 10.7% and 11.4%, under the CCMA RCP4.5 and CCMA RCP8.5 scenarios, respectively, relative to the REF scenario. These results indicated that shifting to the low-carbon pathway while coping with CC impacts is expected to increase sector costs relative to the no mitigation-adaptation scenario (REF) (Fig. 6.b). Thus, the CC adaptation costs for the Java-Bali power system are 2.7 and 3.2 billion USD for CCMA RCP4.5 and RCP8.5, respectively, above the CC mitigation costs (compare CCMA RCP4.5 and CCMA RCP8.5 with CCM in Fig. 6.b). These costs are high, constituting more than half of the budget allocated by the Indonesian Government for CC mitigation and adaptation for all sectors in 2017. These additional costs are due to the extra installed capacity for coal, solar PV, and wind power that are necessary to cope with future CC.

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[4] Assuming annual GDP growth of 4.5%.

5. Discussion

The integration of CC mitigation and adaptation objectives into simulations of the Java-Bali power system expansion revealed the following findings. First, the Java-Bali technology composition will be significantly altered, driven by the constraints set in LEAP, including the minimum renewable energy share and adverse CC impacts. Second, the Java-Bali installed capacity will need to increase to meet the climate-induced increases in electricity demand and to compensate for losses in the reliability of Java-Bali power generation, due to new climate conditions. Finally, although CO_2 emissions will drop with mitigation efforts, the total costs of electricity production are expected to increase by 11.4% in 2050, due to mitigation and adaptation measures.

The NRE targets are expected to force the power system to shift to a low-carbon pathway, resulting in a 34% reduction in CO_2 emissions by 2050. The primary driver of the energy transition in Indonesia is expected to be solar PV, due to its vast remaining exploitable potential, whereas the exploitable potential of other renewables, such as hydro and geothermal, are limited. Likewise, solar PV is also expected to play a significant role in compensating for reduced capacity and energy generation caused by adverse CC impacts, especially under the CCMA RCP4.5 scenario. However, under the higher-temperature change scenario (CCMA RCP8.5), solar PV is expected to have reduced reliability, which will likely be compensated by wind power. However, the rapid deployment of solar PV will also produce waste, generated by retired solar PV systems, associated with the potential leaching of hazardous substances (e.g., lead and cadmium). PV recycling has been suggested as a potential method for preventing these environmental impacts, increasing CO_2 savings [73], and decreasing the energy payback time [74].

Meanwhile, coal is expected to play significant roles in satisfying the climate-induced increases in electricity demand and compensating for declines in power-generating capacities under both CCMA scenarios, resulting in increased CO_2 emissions compared with the CCM scenario. These findings clearly show the interplay between CC mitigation and adaptation objectives and suggest that CC impacts might hinder the CC mitigation efforts of the power system, providing the data-supported quantitative estimate for the hypotheses presented in the literature [75,76,3].

Because CC impacts are unavoidable due to past CO_2 emissions and delayed mitigation actions, these findings suggest several courses of action for policymakers. First, the recognition of the power sector's vulnerability to CC should be a key policy priority, allowing the sector to prepare adaptation action plans and to further integrate these plans into national adaptation strategies. Second, sufficient budget allocations are necessary to facilitate the power sector's adaptations to CC. Since the power sector's adaptations for CC are likely to hinder CO_2 mitigation efforts, a nexus between mitigation and adaptation policies should be exploited in the national budget allocation. Finally, more considerable efforts are necessary to conduct detailed investigations of the CC impacts on individual power plants, including full analyses of the costs and benefits of their adaptations, which may include local investments to prevent reductions in capacity factor and efficiency at individual vulnerable power plants.

6. Conclusions

The primary goal of the present study was to integrate both CC mitigation and adaptation objectives into simulations of a long-term power system expansion. We use Indonesia as an example of a developing country that is currently struggling to meet its electrification needs. The primary power system, Java-Bali, was the focus of this study. Four scenarios for the Java-Bali power system expansion from 2018 through to 2050 were analyzed, including a reference scenario, a CC mitigation scenario, and two scenarios that integrate CC mitigation and adaptation. For all CC mitigation scenarios, the renewable energy targets declared by the Indonesian government, which aim to increase the share of new and renewable energy to 23%, in 2025, and to 31%, in 2050, were used.

The impacts of CC on power supply and demand were quantified using various methods. The WEAP model was used to quantify CC impacts on hydropower availability, and empirical data from fieldwork were combined with reports from the literature to assess the CC impacts on TPPs and electricity demand. The estimated impacts included changes in HEPP capacity factors, reductions in CFPP efficiencies and capacity factors, reductions in NGPP capacity factors, reductions in solar PV generating capacities, and increases in electricity demands. Furthermore, these quantified impacts were integrated into the Java-Bali power system expansion simulation using LEAP. The simulation results were discussed in terms of installed capacity, electricity mix, costs, and CO_2 emissions.

This study provided insight into the economically optimal options for electricity generation by the Java-Bali power system under various CC mitigation-adaptation scenarios. CC-associated impacts on both supply and demand were considered. Although this study did not address the CC impacts for all types of power plants, the results indicated significant deviations from the REF scenario for installed capacity, electricity generation, and the total costs of electricity production, which were attributable to CC mitigation and adaptation strategies. Although the impacts of extreme weather events were excluded, interestingly, the costs of power system adaptations to gradual changes in climate variables, such as temperature and precipitation, were found to be comparable to the costs of CC mitigation.

The methodological approach utilized by this study could be replicated by other attempts to analyze the interplay between CC mitigation and adaptation in the power sector. The present study, however, has several limitations, primarily with regards to the assessment of CC impacts on power generation. First, the projected CC impacts on the Indonesian power sector are preliminary, driven by assessments found in the literature, rather than case-specific, downscaled, CC scenarios. However, this secondary data set provided the basis for an initial evaluation of the CC impacts on the power sector. Furthermore, this study generalized the impacts of CC on CFPPs and HEPPs based on our fieldwork data from several power plants. Future work should focus on collecting detailed data for individual power plants to assess the site-specific costs of CC and possible adaptation solutions. Second, our modeling approach did not include the impacts of extreme weather events, which may intensify under future CC conditions, causing physical infrastructure damage, energy losses, and indirect effects, such as business interruption. Exploring these possibilities would be a fruitful area for further work. Third, due to data limitations and the scope of LEAP, CC impacts on transmission and distribution of electricity were excluded from this assessment while they appear to be significant [44]. Further research should quantify the CC impacts on all components of the power sector: generation, transmission, and distribution. Finally, this analysis relied on global CC projections, which are highly uncertain. Therefore, the modeling of CC impacts on electricity supply and demand performed in this study are inherently uncertain, based on the chosen CC scenarios.

Despite these limitations, this study provided a methodological framework for performing an integrated analysis of CC mitigation and adaptation strategies for the power sector, allowing the interplay between CC mitigation and adaptation to be assessed, which is crucial for developing optimal mitigation and adaptation strategies. This framework can be extended to account for other CC impacts, such as extreme weather events, the impacts of gradual changes in climate variables on transmission and distribution networks, and the impacts on other types of electric power technologies, such as wind power, geothermal, nuclear, and storage technologies.

CRediT authorship contribution statement

Kamia Handayani: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Tatiana Filatova:** Conceptualization, Supervision, Writing - review & editing. **Yoram Krozer:** Conceptualization, Supervision. **Pinto Anugrah:** Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Overview of the LEAP energy system model

The essential features of LEAP for addressing the primary goal of this article 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. A1). 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 article, is the added capacity and electricity generation for each technology, CO_2 emissions, and costs.

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 technology and environmental database that allows the calculation of CO2 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 article, 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.

One limitation in LEAP is that the model does not provide for the expansion of transmission and distribution lines. Hence, the power system expansion simulation in this article neglected constraints in the T&D networks, assuming that electricity can be transmitted at any time to any load station. Further modeling works will have to cover transmission capacity and spatial analysis of each power plant and substation.

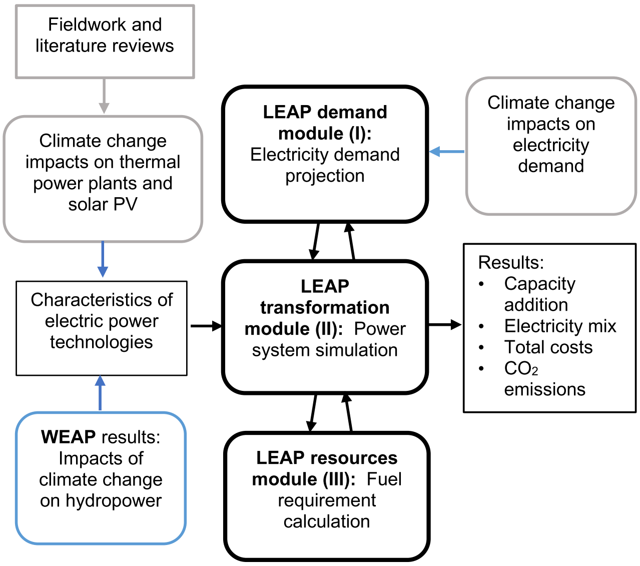

Fig. A1. LEAP-WEAP model for Integrated climate change mitigation-adaptation analysis.

Appendix B. Projection of temperature and precipitation changes

(See. Tables B1–B2)

Table B1
Historical and projected changes in temperature.

Month	Temperature (°C) 1986–2005	Projected changed			
		2020–2039		2040–2059	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
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 B2
Historical and projected changes in precipitation.

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 C. Assumptions for the LEAP model

(See. Table C1)

Table C1
Renewable energy potential and current practice in Indonesia.

Renewable	Potential in Gigawatt		Renewable deployment by 2018, total Indonesia		Sources
	Total Indonesia	Java- Bali islands	Installed capacity (Gigawatt)	Renewable utilization (%)	
Hydro	75	4.2	5.4	7.2%	DEN [55], ESDM [77]
Hydro pumped storage	4.3	3.9	0	0.0%	PLN [78], ESDM [77]
Mini hydro	19.4	2.9	0.4	2.1%	DEN [55], ESDM [77]
Geothermal	17.5[a]	6.8[a]	1.9	11%	DEN [55], ESDM [77]
Biomass	30	7.4	1.8	6.0%	DEN [55], ESDM [77]
Solar	5374[b]	2747[b]	0.06	0.0%	Kunaifi and Reinders [79], ESDM [77]
Wind	60.6	24.1	0.14	0.2%	DEN [55], ESDM [77]

[a] excluding the speculative and hypothetical potential.
[b] in Gigawatt peak.

Appendix D. Assumptions for projecting climate change impacts on the electricity supply

(See. Figs. D1–D2)
(See. Table D1)

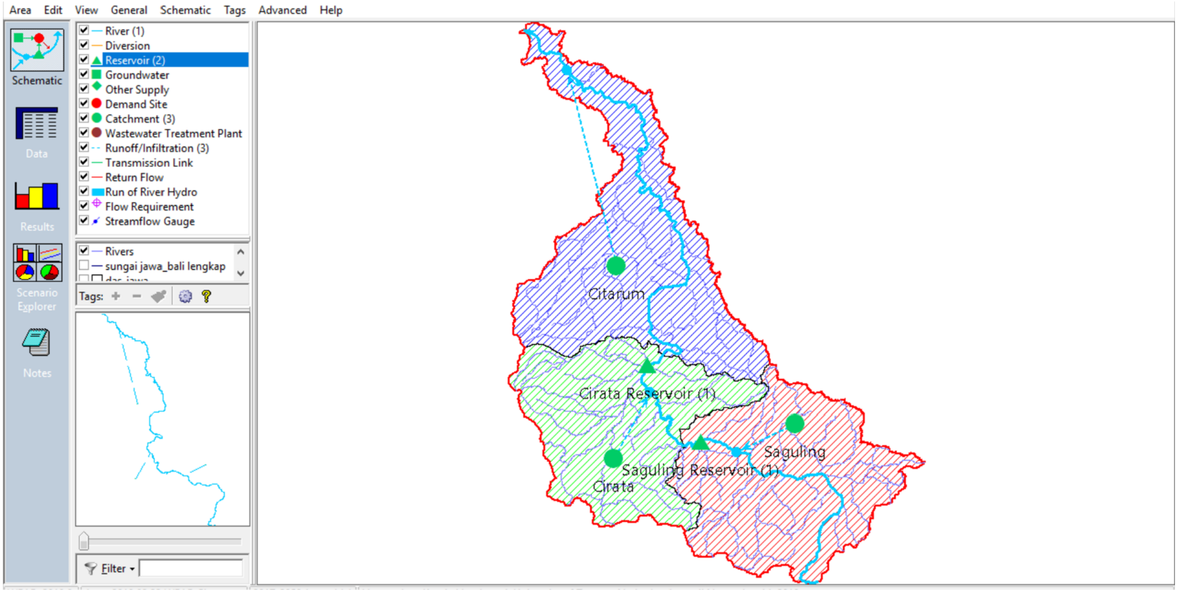

Fig. D1. Schematic view of water demand and supply of the Citarum WEAP model. Source: own simulations.

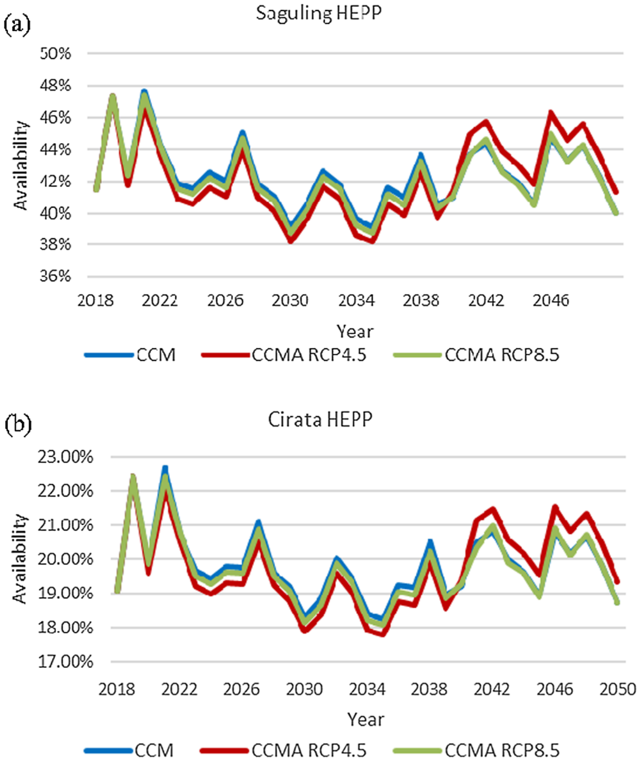

Fig. D2. The average annual capacity factor of HEPPs under CCM and CCMA scenarios: (a) Saguling HEPP; (b) Cirata HEPP. Source: WEAP estimates.

Table D1
Input data for the Citarum WEAP model.

Input Data	Value	Sources
Catchment		
Map	Fig. D1	KLHK [80], BIG [81]
Area	Saguling: 222 thousand ha, Cirata: 416 thousand ha	Own calculation based on geospatial analysis
Precipitation (mm)	Monthly, 1948–2017	Sheffield et al. [82], PLTA Cirata [83], and PLTA Saguling [84]
Temperature (°C)	Mean monthly air temp, 1948–2010	Sheffield et al. [82]
Wind speed (m/s)	Monthly, 1948–2010	Sheffield et al. [82]
Total Storage Capacity	Cirata: 2,165 million m^3, Saguling: 875 million m^3	PLTA Cirata [83], PLTA Saguling [84]
Max Turbine Flow	Cirata: 1,080 m^3/s, Saguling: 219.2 m^3/s	PLTA Cirata [83], PLTA Saguling [84]
Tailwater Elevation	Cirata: 84 m, Saguling: 252 m	Kasiro et al. [85]

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