Energy Transition in the Kalimantan Power System:

Combining Spatiotemporal Power System Modelling with Energy Justice Analysis

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MSc Complex Systems Engineering and Management

Delft University of Technology

July 2022

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Master thesis submitted to Delft University of Technology
in partial fulfilment of the requirements for the degree of

Master of Science

in **Complex Systems Engineering and Management**

Faculty of Technology, Policy, and Management

by

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To be defended in public on July 28th, 2022

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Acknowledgements

This thesis concludes my journey as a master's student in Complex Systems Engineering and Management at Delft University of Technology. A two-year journey passes by in a blink of an eye with so much left to say. Many lessons have been learned during my time here. Be it academic or life experiences. And a lot of things happened either ups or downs. I am grateful that these had changed me in a good way. That there are always blessings in disguise.

First, I would like to thank my small family, Puspa Andita Rahman and Sanabel Amaya Hilman, for the persistent support and everlasting love throughout these difficult years of living apart. I would also like to thank my parents and other family members for the prayer and care from afar.

To my graduation committee, I would like to express my utmost gratitude for your precious guidance and support since the beginning of this project. Thank you Prof.dr. Kornelis Blok for the critical and constructive feedback that brought the best out in me. Thank you Dr. Jenny Lieu for the generous and warm mentorship that helped me carry on with the complexity of this project. Thank you Jannis Langer for the constructive and meaningful support that made me always try to do better. Thank you Dr. Abidah Setyowati for the valuable and insightful suggestions that opened my mind from the other perspective. Thank you everyone for willing to supervise and mentor me with all my flaws.

I would also thank the Faculty of Technology, Policy, and Management for the financial support. Thank you for trusting me to receive the Faculty Scholarship two years ago. Without this support, I would not be able to be here in Delft.

And last but not least, I would like to thank my superb friends at Delft and back home in Indonesia. Exceptionally, my fellow Indonesian students, fellow CoSEM/TPM students, and housemates. Thank you for your loving and compassionate support since the day we met. Thank you for the laughs. And thank you for being my friends and groupmates throughout my two-year episode at TU Delft. I hope our journeys cross paths again someday.

This thesis is not the end of my journey. I hope this is only the beginning of the wonderful life ahead. Cheers!

Hilman Dwi Putra

Delft, July 2022

Executive Summary

The relocation of Indonesia's capital city from Jakarta to Kalimantan is estimated to cause growing electricity demand in Kalimantan due to the rapid increase in population and economic activity. Besides, the Indonesian government announces a national strategy to achieve net-zero emissions through energy transition and justice. This is to raise the RE share in the electricity mix from 16% to 43% by 2050. Raising the RE share to this level is substantial to realize the LTS-LCCR 2050. And going beyond this level can be essential to accelerating the net-zero emission goal. However, this ambitious target requires transformational changes in the energy system, which needs to address various potential trade-offs that emphasize justice and sustainability. There are no extensive studies that assess the impact of this strategy and the growing demand for the Kalimantan power system, while the current government's strategies may not address the issue of justice and sustainability.

Therefore, this thesis project, in collaboration between Delft University and Technology (TU Delft) and Institut Teknologi Bandung (ITB), aims to conduct a techno-economic and energy justice analysis of the power system with the main research question:

"What is the optimum configuration of renewable energy integration in the interconnected Kalimantan power system in 2050 to achieve net-zero carbon emissions while considering some energy justice parameters?"

The research is conducted using power system modelling as well as qualitative analysis. A conceptual model of the Kalimantan power system will be developed in a modelling and simulation tool. The model will be formulated as an optimization of generation problems to assess optimum solutions for generation and transmission investments while satisfying all constraints. Based on the optimization and interview results, the relationships between techno-economic states of the system in 2050 and energy justice principles are evaluated to provide recommendations regarding how to design power system expansion in Kalimantan that optimizes techno-socio-economic parameters.

This research concludes that RE integration and transmission system interconnection could lower the levelized system costs in 2050. The LCOE from the Kalimantan power system model could decline from 72 USD/MWh in 2021 to 31 USD/MWh in 2050. The electricity generation mix could evolve from 90% fossil fuel in 2021 to 100% RE plus battery storage in 2050. The mix in 2050 potentially consists of approx. 76% hydro, 11% solar, 9% biomass, and is supported by 3% battery storage. It includes achieving net-zero carbon emissions and improving energy justice in terms of affordability, availability, and intra- and inter-generational equity in the Kalimantan power system. The future LCOE becomes cheaper, the supply meets all the demand, the electricity access is expanded, and the emission level plummets.

Despite its positive results, this research has several limitations to be addressed in future research. Firstly, the actual demand profile of Kalimantan is not openly available. Secondly, the spatial resolution of some RE potential data such as hydro and biomass is lower than that of solar and wind. Thirdly, the variability of dispatchable renewables such as hydro and biomass is not taken into account, however, the expert interview helps validate the result of this simplification. Fourthly, some other available technologies such as PHES are not included in the model. Lastly, the model optimization and interviews cannot capture a number of important things such as rolling blackouts in some specific regions, unmet demand from low electrification ratio, and the perception of the most vulnerable groups.

To improve this research, there are three recommended research avenues to be explored in the future. First, high-spatial and high-temporal hydro and biomass potential will be useful for exploring their specific potential sites and variability of resource availability in Kalimantan. Second, qualitative analysis can be implemented to incorporate the most vulnerable group in the development of RE in the Kalimantan power system in order to assure the positive impact of the energy transition on energy justice. Third, macroeconomic and land use simulation models to explore future policies related to the technical development of RE and its socio-economic impact.

List of Abbreviations

ADB	Asian Development Bank
ASEAN	Association of Southeast Asian Nations
BPP	*Biaya Pokok Penyediaan Pembangkitan* (Electricity Generation Basic Cost)
BPS	*Badan Pusat Statistik* (Statistics Indonesia)
CBS	*Centrale Bureau voor de Statistiek* (Statistics Netherlands)
CCS	Carbon Capture and Sequestration/Storage
CF	Capacity Factor
CO_2	Carbon dioxide
DSO	Distribution System Operator
EIA	United States Energy Information Administration
ESDM	*Kementrian Energi dan Sumber Daya Mineral* (Indonesia's Ministry of Energy and Mineral Resources)
Govt	Government
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IESR	Institute for Essential Services Reform
IPP	Independent Power Producer
IRENA	International Renewable Energy Agency
kg	Kilogram
KLHK	*Kementrian Lingkungan Hidup dan Kehutanan* (Indonesia's Ministry of Environment and Forestry)
kW	Kilowatt
kWh	Kilowatt hour
LCOE	Levelized Cost of Electricity
MW	Megawatt
MWh	Megawatt hour
NEC	National Energy Council (*Dewan Energy Nasional*)
NOAA	United States National Oceanic and Atmospheric Administration
PHES	Pumped Hydroelectricity Energy Storage
PLN	*Perusahaan Listrik Negara* (Indonesia's State Electricity Company)
PV	Photovoltaics
RE	Renewable Energy
RUKN	*Rencana Umum Ketenagalistrikan Nasional* (National Electricity Master Plan)
TSO	Transmission System Operator
UBC	University of British Columbia
UN	United Nations
UNESCAP	United Nations Economic and Social Commission for Asia and the Pacific

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Chapter 1

Introduction

1.1 Challenges in future Kalimantan power system

Indonesia is the tenth-largest emitter of greenhouse gases (GHG) in the world (ADB, 2020). In response to the Paris Climate Agreement, Indonesia announces the Long-Term Strategy for Low Carbon and Climate Resilience 2050 (LTS-LCCR 2050). This national strategy seeks to achieve net-zero emissions in 2060 through an energy transition that balances emission reduction, economic growth, justice, and climate resilience development. As of 2019, renewable energy (RE) accounts for only 16% of Indonesia's power generation mix, while the government sets a 43% share of RE in the mix by 2050 (KLHK, 2021). Raising RE share to this level is thus substantial to realize the LTS-LCCR 2050. And going beyond this level can be essential to accelerating the net-zero emission goal. However, this ambitious target requires transformational changes in the energy system, which needs to address various potential trade-offs that emphasize justice and sustainability (KLHK, 2021).

In 2019, the Indonesian government also announced a capital city relocation project from Jakarta to Kalimantan which will begin in 2024 to alleviate the burden of sinking Jakarta (Suroyo & Jefriando, 2019). The new capital city will be located within the East Kalimantan region. The population of both the new capital city and other provinces in Borneo Island is expected to grow significantly as the economic activities in these regions develop. The Kalimantan power system will face several challenges in fulfilling the growing demand caused by the rapid increase in population and economic activity while achieving the net-zero emissions target (Nugroho, 2020). This challenge needs to address because phasing out fossil-fuel power plants before the end of their life cycle is both costly and impractical due to the locked-in phenomenon (KLHK, 2021).

The new capital city project also has the potential to address the energy injustice in Kalimantan. In terms of electricity access, for instance, there has been an uneven electricity ratio across the island. East Kalimantan has an electrification ratio of 99%, while Central Kalimantan has a ratio of 94% only (ESDM, 2020). Furthermore, many electrified regions do not receive 24 hours of electricity per day (ABD, 2020). It demonstrates inequity and availability in electricity access in Kalimantan, despite justice being one of the main pillars of Climate Resilience in the LTS-LCCR 2050 (KLHK, 2021). The development of infrastructure of the new capital city project, including power system infrastructure, is expected to improve this situation. This expectation also adheres to the National Electricity Supply Business Plan of State Electricity Company (RUPTL PLN) 2021-2030, in which PLN plans to interconnect and expand the whole Kalimantan power system. Therefore, another challenge faced by the project is determining how to develop energy justice in Kalimantan while achieving the net-zero emissions target in the interconnected power system.

Power transmission and distribution in Indonesia are vertically controlled by PLN as both TSO and DSO (ADB, 2020). A large share of RE integration in the system can generate several challenges for TSO in balancing the supply and demand due to intermittencies and non-dispatchable generation units such as solar and wind energy. Meanwhile, there is a scientific knowledge gap regarding the lack of integrated analysis of the RE integration and power system expansion that incorporates conventional techno-economic parameters and energy justice elements in the Kalimantan power system. A valid RE integration analysis result can provide useful insights to both researchers and policy-makers regarding the impact of RE integration under constraining net-zero emissions while considering energy justice in Kalimantan in the future. Furthermore, accurate demand forecasting can also result in substantial cost saving for the electricity sector (McNeil et al., 2019). It can also provide an output that can be useful for supporting the decision-making process in designing a strategy for future transmission and generation planning in Kalimantan.

1.2 Research objectives

The objective of this research is to conduct the techno-socio-economic analysis of the Kalimantan power system in order to gain insights on how to optimize RE integration in the power system to achieve the RE level beyond the target set by LTS-LCCR 2050 and how energy justice may reciprocally affect RE integration and power system expansion in Kalimantan.

1.3 Research questions

1.3.1 Main research question

The main research question is formulated based on the identification of knowledge gaps in the Kalimantan power system research and the research objective defined in section 1, namely:

"What is the optimum configuration of renewable energy integration in the interconnected Kalimantan power system in 2050 to achieve net-zero carbon emissions while considering some energy justice parameters?"

1.3.2 Sub-questions

Three sub-questions (SQ) are formulated to answer the main research question (RQ):

SQ1. "How can the Kalimantan power system be conceptualized and modelled based on techno-economic and energy justice parameters?"
SQ2. "What is the effect of renewable energy generations on the cost-optimum configurations and energy justice of the Kalimantan power system under constraining net-zero carbon emissions?"
SQ3. "How does the system interconnection evolve and affect the system costs of the Kalimantan power system under constraining demand fulfilment and high electrification ratio?"

SQ1 corresponds to the main RQ regarding the analysis of the Kalimantan power system and data gathering for techno-economic and energy justice parameters. The system boundaries are defined, and the simplification of the real Kalimantan power system is determined based on the scope of this research. SQ2 corresponds to the main RQ regarding optimization of RE integration in the Kalimantan power system. SQ3 corresponds to the main RQ regarding optimization of transmission system interconnection in the Kalimantan power system.

1.4 Research approach

This research implements a modelling approach as well as qualitative analysis. A conceptual model of the Kalimantan power system will be developed in modelling and simulation software. The importance of power system modelling has risen in recent years due to the increase in distributed and fluctuating wind and solar generation, and the increasing electrification of all energy demands (Brown et al., 2018). Energy system models create coherent quantitative descriptions of how energy is converted, transported, and consumed at various scales. Formulating such models as optimization problems helps assess the effect of constraints such as RE capacity expansion on the feasibility or costs of the modelled system (Pfenninger & Pickering, 2018). Therefore, the model will be formulated as optimization problems to assess various combinations of generation and transmission investments to identify the optimum solution while satisfying all constraints (Liu et al., 2013). The main advantage of the modelling approach is that multiple system interventions can be tested in a short time without affecting real-world systems. The main limitation of this approach is that the results of the experiments depend on assumptions and input data, which is known as the garbage-in garbage-out principle. It means that the quality of the output cannot be higher than the quality of the input (Nikolic et al., 2019). This limitation can be addressed by determining input data from official and scientific references.

The approach used in this research consists of four main steps. First, the conceptual design of the Kalimantan power system is modelled within current configurations. The conceptualization phase considers relevant technical, economic, and social, which is energy justice in this context, parameters. The energy justice parameters are defined as demand fulfilment, land use constraints for renewable energy potentials, cost of electricity, and CO_2eq emissions. These are quantified as parts of the techno-economic parameters in the model. The spatial region of the system is also considered because the Kalimantan power system is not yet interconnected entirely and the RE potentials may differ in different regions of Kalimantan. These data are gathered through a literature review. Second, the model is implemented and validated using techno-economic metrics. Third, multiple system interconnection planning and RE penetration levels are implemented and simulated using hourly electricity supply and demand profiles. Various RE technologies are considered based on their potential in the Kalimantan regions as well as their technological maturity. Fourth, based on the simulation results, the relationships between techno-economic states of the system in 2050 and energy justice principles are evaluated to provide recommendations regarding how to design power system expansion in Kalimantan that optimizes techno-economic and energy justice parameters.

1.4.1 Positionality and intersectionality of the research approach

A positionality statement is a description of the author's identity in society related to a particular project. Intersectionality refers to particular forms of intersecting oppressions such as intersections of race, gender, and nation (UBC, n.d.). The author of this research was born and grew up in a satellite city within the Jakarta Metropolitan Area in Indonesia, with easily-accessible and relatively reliable electricity service. He came from a multi-ethnic family living in a neighbourhood where low-, middle-, and high-income households reside in the same region. He took the Energy track from the MSc Complex Systems Engineering and Management with a specialization in Advanced Modelling, Gaming, and Design at TU Delft in the Netherlands. This academic background introduced him to complex technical, economic, and social issues of the energy transition. His research focuses on modelling and analysis of the energy transition that brings together technical, economic, and social aspects.

1.5 Alignment to Complex Systems Engineering and Management

This research addresses the socio-technical and economic complexity of the energy systems in Kalimantan, where many actors with diverse values from both the public and private sectors are involved. Its research engineering component is the power generation and transmission system. System dynamics modelling and qualitative analysis methods will be used to implement the system engineering approaches. The academic contribution of this research is the novelty of analysis methods that combine spatiotemporal power system modelling with energy justice analysis.

1.6 Thesis outline

This thesis report is divided into four parts. Part I is the preliminary step that encompasses Chapter 2 and Chapter 3. Chapter 2 presents the literature review to address the knowledge gaps within this field of study. Chapter 3 explains the methodology used in this research. Part II consists of Chapter 4 which encompasses the techno-economic modelling and analysis of the energy transition in the Kalimantan power system. Part III consists of Chapter 5 which encompasses the energy justice analysis that intercorrelates with the techno-economic analysis presented in Chapter 4. Part IV consists of Chapter 6 and Chapter 7. Chapter 6 presents the discussion related to the results and limitations elaborated in Part II and Part III and provides policy recommendations for the energy transition in Kalimantan. Chapter 7 summarises the insights obtained from this research by answering the main research question as well as presents the summarised research limitations and future research recommendations. The thesis outline is presented in **Figure 1**.

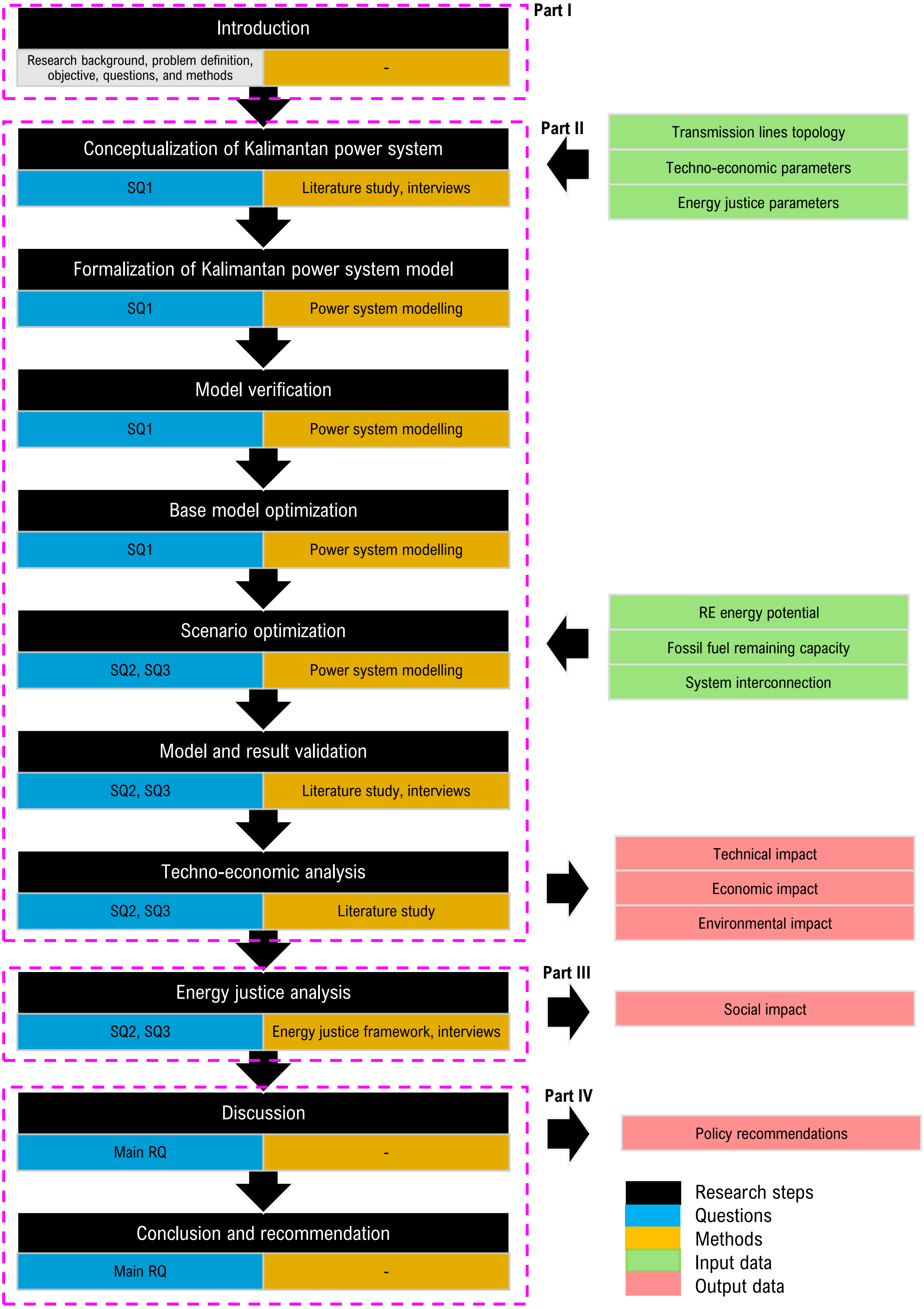

Figure 1 Thesis outline

Chapter 2

Literature Review

2.1 Search Methodology

Various search methods were conducted. Relevant scientific articles were explored by computer searches through Scopus and Google Scholar. Only articles written in English and Bahasa Indonesia were explored. Keywords were used i.e.:

- Kalimantan AND power AND system
- Sistem AND jaringan AND listrik AND Kalimantan
- Energy AND justice

The results were followed by filtering "relevance" to sort out the articles that were most closely related to the keywords. The publication year is also filtered to up to 5 years because the review should be based on recent situations in the power systems and energy justice topics. Some articles were also gathered based on project advisors' recommendations. Following that, manual evaluation was conducted by reading the abstract and conclusion and skimming through the other chapters. The criteria for manual evaluation were the extent of subjective relevance with the Indonesian context and with the energy transition. The criteria include the incorporation of Kalimantan or Indonesia in the publication's main topic and of Global South context if Indonesia is not explicitly included in the publication. By using these methods, five articles about Kalimantan power systems and five articles about energy justice were selected.

2.2 Literature Review Results and Knowledge Gaps

The ten reviewed papers are presented in **Table 1**. It summarizes the main findings of the systematic literature review i.e. key contributions and recommendations of their research. The knowledge gaps are then derived from these findings.

2.2.1 Literature review results

The first insight from the findings is related to the plan to interconnect the whole Kalimantan power system. Based on the five reviewed articles about the Kalimantan power system, the West Kalimantan power system is still disconnected from the rest of the Kalimantan power system. As a result, Jintaka et al. (2018) and Sutardi et al. (2019) conducted their research on the West Kalimantan power system only. On the other hand, Ardyono et al. (2019) researched the optimization of the entire Kalimantan power system interconnection, but only focused on the technical impact on electrical system stability. Their research is consistent with the policy recommendation mentioned in Nugroho (2020) regarding the need to build power system interconnection for the entire Kalimantan. Furthermore, Widodo & Putri (2020) provided a research recommendation for more comprehensive cost optimization of power transmission and generation investment in Kalimantan using more relevant variables. No comprehensive techno-economic analysis that co-optimizes Kalimantan's power system interconnection from the capacity planning perspective is addressed in the reviewed articles. Meanwhile, there are a plenty of this type of scientific articles related to Jamali power system located at the Indonesia's primary islands of Java, Madura, and Bali.

The second insight from the findings is related to the RE integration in the Kalimantan power system. Four out of the five reviewed articles on the Kalimantan power system considered RE as a part of their research. Only Widodo & Putri (2020) stated that RE was not incorporated in their research. Ardyono et al. (2019) and Sutardi et al. (2019) mentioned their interconnection analysis is related to facilitating the increase of RE generation in the energy mix, although RE was not used as a variable in their research. On the other hand, Jintaka et al. (2018) provided a research recommendation to estimate the maximum allowable intermittent RE penetration levels in the West Kalimantan power system. Their result showed that the maximum variable RE penetration levels to the West Kalimantan grid by considering system frequency and voltage limit in peak hours and off-peak hours are 16% and 7.98%, respectively. Furthermore, Nugroho (2020) provided a recommendation to prioritize the expansion of RE capacity in Kalimantan, highlighting the large potential of large-scale hydropower in the region. Yet, a comprehensive techno-economic analysis of RE integration in the Kalimantan power system is not provided in any reviewed articles.

Table 1 Key contributions and recommendations of the reviewed papers

Authors	Year	Key Contribution	Recommendations	Methods
Sutardi et al.	2019	Strategy for designing stable operations of Sabah-West Kalimantan power system interconnection	N/A	Power flow optimization modelling
Ardyono et al.	2019	Stability analysis of interconnected transmission development in Kalimantan	N/A	Power system stability analysis
Nugroho	2020	Strategy for fulfilling energy demand in new capital of Indonesia in Kalimantan	- Development of clean, renewable energy - Use of local energy sources - Large scale hydropower construction - Interconnection of transmission lines to connect whole Kalimantan	Qualitative analysis
Widodo & Putri	2020	Insights about the lowest costs of power generation and transmission for supporting investment decision-making in Kalimantan power system	- Identification of more relevant variables to make the system analysis more detailed and comprehensive	Game theory modelling
Jintaka et al.	2018	Impact estimation of renewable energy penetration on grid stability in West Kalimantan power system	- Estimation of maximum allowable intermittent renewable energy penetration level	Power system stability analysis
Fathoni et al.	2021	Insights about how the dominance of apolitical, top-down, and techno-managerial framing of community-based renewables might result in the perpetuation of energy injustices	- Energy justice analysis in the developing world context	Qualitative interview, field observation
Setyowati	2020	Insights about multiple barriers constraining the mobilization of private finances to support renewable rural electrification in Indonesia	- Predictability and certainty improvement in the renewable energy regulations - Policies reformation to support financing the energy transition - Mechanisms to address the challenges of financing renewable rural electrification	Qualitative interview, field observation
Setyowati	2021	Insights about interpretation of energy justice vision in Indonesia's policies and programs reproduces energy injustices	- Policies reformation to encourage and incentivize diversity of solutions to address energy poverty beyond large-scale and on grid solutions	Qualitative interview
Castán Broto et al.	2018	Situated analysis of energy justice in the Mozambique energy transition, a country that faces massive energy access challenges	- Research on the methods for understanding energy justice dilemmas to enable a sustainable future	Qualitative analysis
Rasch & Köhne	2017	Insights about the concept of energy justice from how people experience and construct energy justice from below	- Considering the local perception of what is just and unjust in terms of energy production - New energy projects development based on local practices of energy justice - Recognition of involved groups in the decision-making process	Case study, qualitative interview

The third insight from the findings is about energy justice. Fathoni et al. (2021) and Setyowati (2020) conducted their energy justice research in Indonesia, whereas the other three articles conducted their energy justice research outside of Indonesia. Setyowati (2020) identified multiple barriers to private financing that impede renewable rural electrification in Indonesia, highlighting the lack of access to quality, reliable electricity. Fathoni et al. (2021) mentioned the dominance of techno-economic considerations behind energy decision-making that overlook social justice concerns. They made a research recommendation to investigate energy justice in the context of the developing world. Furthermore, Castán Broto et al. (2018) argued the limitation of universalist energy justice frameworks, particularly when they are applied in the Global South. They suggested situated and particularistic analysis of energy transition is needed when deploying the framework in those countries. Moreover, Setyowati (2021) mentioned that energy policies in Indonesia need to encourage and incentivize a diversity of solutions to address energy poverty beyond large-scale and on-grid solutions. It becomes interesting to compare her insights with the large-scale grid-connected Kalimantan power system modelling optimization results. In addition, Rasch & Köhne (2017) provided a research recommendation to develop new energy projects based on local energy justice practices.

2.2.2 Knowledge gaps

These insights can be perceived as a knowledge gap regarding the lack of integrated analysis of the power system expansion and renewable energy integration that incorporates conventional techno-economic parameters and energy justice elements in the Kalimantan power system, particularly related to the energy transition. It is necessary to notice that all evaluated articles, either the ten reviewed articles or the excluded articles during the literature research, only address some of these elements in their research. Besides, there have not been found any scientific articles related to Kalimantan that incorporate both techno-economic and energy justice elements based on power system modelling analysis. Therefore, this thesis aims to address this gap by providing a novel scientific methodology that incorporates these energy justice elements in the analysis of the Kalimantan power system optimization. This novelty includes combining spatiotemporal power system modelling that focuses on a techno-economic perspective with energy justice analysis that focuses on a social perspective.

2.3 Definition of Core Concepts

Optimization explores possible combinations of generation and transmission investments in power systems planning to identify the optimum solutions in terms of cost or other objectives while satisfying all technical, economic, environmental, and policy constraints (Liu et al., 2013). Optimization of power systems is modelled in computer-aided tools. An optimization model is useful where power utilities are vertically integrated, which the Indonesian power system is, because it identifies less costly solutions by considering the interaction of generation and transmission (Liu et al., 2013). In this research, the cost solution is described in the term of LCOE. LCOE is an estimation of the revenue required to build and operate a power generator over a specified cost recovery period (EIA, 2021). Moreover, optimization also facilitates integrated and concurrent assessment of all planning alternatives, including supply-side options, demand-side management, and transmission. Therefore, it is highly useful for power system expansion planning that integrates RE generations (Liu et al., 2013).

Energy justice is an important analysis to understand how values are incorporated into energy systems (Sovacool & Dworkin, 2015). Energy justice seeks to apply justice principles to energy policy, energy production and systems, energy consumption, energy activism, energy security, the energy trilemma, political economy of energy, and climate change (Jenkins, 2016). Furthermore, it can assist energy planners and consumers make better energy decisions. Sovacool & Dworkin (2015) specified three frameworks for energy justice as: 1) a conceptual tool, 2) an analytical tool, and 3) a decision-making tool. In this research, energy justice as a decision-making tool is to be used because it can assist energy planners and consumers in making more informed energy choices (Sovacool & Dworkin, 2015).

In addition, they described different elements of energy justice as a decision-making tool i.e. availability, affordability, due process, good governance, prudence, intra- and intergenerational equity, and responsibility. However, due to the scope of this research, only availability, affordability, intragenerational equity, and intergenerational equity in the Kalimantan power system are evaluated.

Availability involves the ability of the system to guarantee sufficient energy resources when needed. It transcends concerns related to the security of supply, sufficiency, and reliability. Affordability encompasses stable and equitable energy prices that do not require lower-income consumers to expend disproportionally more of their income on essential services. It means the energy bills do not overly burden consumers. Intragenerational equity implies that present people have a right to fair access to energy services, including clean energy defined in the UN Sustainable Development Goals 7. It also encompasses the conditions such as unpolluted air, water, and other environmental goods. Intergenerational equity means that future generations have a right to a good life unhindered by the harm our energy systems inflict on the world today. Consequently, each of us has the responsibility to prevent climate change and make a strategic investment to increase the resilience of communities (Sovacool & Dworkin, 2015). Therefore, these principles are strongly linked to the decision-making about optimization of power system planning that spans multiple human generations.

Chapter 3

Methodology

3.1 Model conceptualization and data gathering

The first phase of this research is related to SQ1. Various data are gathered to conceptualize the Kalimantan power system. First, the Kalimantan's topological transmission system data are gathered from official references such as PLN Electricity Supply Business Plan (RUPTL PLN) and ESDM Geoportal. Only 150kV transmission lines plus a 275kV transmission line for the import are considered in the model. Because these are the highest transmissions lines presence in Kalimantan and inclusion of lower transmission lines are out of the scope of this research. The power system will be divided based on the actual provincial division in Kalimantan because each province may have different RE potentials and demand profiles, due to differences in population and economic activities with the latter.

To reduce the computational complexity, the number of substations (nodes) in the power system network will be simplified by using the k-means clustering method. The objective of this method is to produce clusters of variables with a high degree of similarity within each cluster and a low degree of similarity between clusters. The main limitation of this method is a bias to create clusters of equal size that do not represent the group distribution in the data (Morisette & Chartier, 2013). Therefore, the result of clustering computation will consider the provincial borders of Kalimantan to get centroids that are located within the actual provincial borders.

To further conceptualize the system, data regarding technical parameters (thermal capacity limit, generation capacity, capacity factor, ramp limits, and efficiency) and economic parameters (capital costs, operational costs, marginal costs, electricity prices, hourly electricity demand profile, and demand growth) are gathered from scientific articles and official documents such as LTS-LCCR 2050 (KLHK, 2021), RUPTL PLN 2021-2030 (PLN, 2021), and energy outlook and reports from ESDM (ESDM, 2022a; ESDM, 2022b; ESDM, 2021; ESDM, 2020a; ESDM, 2020b; ESDM, 2019; ESDM, 2016), scientific research institutions, and consultancy firms.

In this research, energy justice parameters used in the modelling approach are assumed as follows:

1. Intragenerational equity is comparable to the electrification ratio, weighing up the electricity demand with the population of particular regions, and the current state of CO_2 emission level.
2. Intergenerational equity is the future changes in CO_2 emission level and system costs in terms of LCOE and levelized systemwide capital cost.
3. Availability is the reliability of the electricity supply portrayed by the fulfilled demand in the hourly economic dispatch.
4. Affordability is the electricity prices related to the systemwide LCOE.

The number of unmet electricity demands related to the electrification ratio is assumed as the product of the total population in a province and its inverse electrification ratio. Electricity demand per person is assumed as the total electricity consumed from PLN transmission system in a year in a province divided by its total population. The future changes in systems costs are quantified as the difference in LCOE in 2021, 2030, and 2050. The future changes in CO_2eq emissions level are quantified as the difference in systemwide CO_2eq emissions (kg_{CO2eq}/MWh) in 2021, 2030, and 2050. The reliability of the electricity supply is quantified as a constraint for the system to fulfil all demands in 8760 hours per year. It means the simulation is configured to stop working if an unmet demand occurs. Affordability is quantified as regulated electricity tariffs that can be afforded by Kalimantan's residents compared to the LCOE obtained from the optimization results. These assumptions will be validated by qualitative interviews with ten stakeholders and literature reviews.

3.2 Model formalization

The power system network that consists of buses and lines is formalized using the Python for Power System Analysis (PyPSA) packages in Python to perform the network simplification using k-means clustering. The number of buses is reduced to simplify the energy regions in Kalimantan based on the centroids and regional borders consideration. The simplified power system is then formalized and configured through system dynamics modelling in Python using Calliope. Calliope is a framework to build energy system models with arbitrarily high spatial and temporal resolution as well as a scale-agnostic mathematical formulation. The models create coherent quantitative descriptions of how energy is converted, transported, and consumed at various scales. The optimization problems of Calliope models are used to assess the effect of constraints on the feasibility or cost of the modelled system (Pfenninger & Pickering, 2018). The main components included in the model are fossil-fuel generators, intermittent and non-intermittent RE generators, electricity storage units, and the combinations of direct and alternating current electricity networks. The main limitation of this method is numerous assumptions need to be made when there is a lack of data. The conceptual model is also prone to information loss, depending on to what extent the system boundaries and model resolution are determined.

3.3 Model verification

The formal model is verified by code-driven testing. First, the model is run with minimal spatial and temporal resolution to check whether the model behaves as intended and generates the expected output. Second, the code is extended to configure more components in the model gradually. Each configuration is tested. Several assumptions configured in the model are also tested to check whether the selected assumptions produce the expected output. After all the tests succeed, the full model is run using prompt/terminal to obtain the results and visualizations. Iterations are made during the model verification step.

3.4 Renewable energy integration in the model

The second phase of this research is related to SQ2. Georeferenced RE potentials for biomass, solar, wind, geothermal, hydro, and ocean energy are collected from scientific publications. Furthermore, energy storage technology such as utility-scale lithium-ion batteries and PHES are taken into account. Moreover, the potential of nuclear energy in the future is also considered in the assessment because it does not generate carbon emissions. Estimations are made when there are no sufficient spatial resolution data of the RE potentials. Then, these data will be formalized and integrated into the Kalimantan power system model. The main limitation of this method is numerous assumptions need to be made when there is a lack of data. In addition, some RE technologies, such as ocean power, does not reach extensive commercialization yet. Several assumptions need to be made to determine their techno-economic parameters within the model time span.

3.5 Model optimization

The third phase of this research is related to SQ2 and SQ3. Power generations and transmission line systems are optimized in three different years i.e. 2021, 2030, and 2050. There is no significant variability in the present models (2021 and 2030) because these models are based on the configurations published by RUPTL PLN 2021-2030 and other Indonesian government published plans regarding the Kalimantan power system i.e. electricity generation mix, electricity generation per province, electricity power plant per types of energy carrier per province, and transmission network expansion plan. The 2050 model is configured using variables related to the maximum nominal capacity of each power plant in each energy region. Thus, the nominal capacity of non-fossil fuel power plants in each region is determined by the most optimum solutions with respect to their respective theoretical potential, depending on the scenarios. The optimization process is run in Anaconda Prompt. The limitation of this method is the insights may not present the whole picture because the analysis is conducted based on simulated data in a simplified system, not based on actual data from field observation.

3.5.1 Cost-optimum baseline scenario

The cost-optimum baseline scenario consists of the baseline models of 2021 and 2030 and the 2050 model configured with respect to RUPTL PLN 2021-2030 (PLN, 2021) and other Indonesian government published plans such as LTS-LCCR 2050 (KLHK, 2021) and RUKN 2019 (ESDM, 2019). It means the 2050 baseline model includes remaining fossil fuel power plants that have not yet reached their end of life in 2050 while excluding power plants that have passed their end of life. Microsoft Excel VBA is used to determine which existing power plants are to be kept or removed in 2030 and 2050 based on their lifetime. The commissioning year of these power plants is derived from data from ESDM Geoportal (ESDM, 2022b) and RUPTL PLN 2021-2030. A number of power plants with no commissioning year data are also excluded from the 2050 model to avoid misestimation. The maximum capacity factor of all power plants in 2050 is constrained to be 99% at maximum so as to roughly consider the time used for maintenance. Then, these models are run to solve the optimization problem with the objective to minimize the system cost (LCOE).

3.5.2 Cost-optimum with coal price cap annulment scenario

The coal price cap annulment scenario is mostly the same as the cost-optimum baseline scenario. The only difference is that the coal price for coal power plants is changed from 3.14 USD/GJ to 5.65 USD/GJ. The coal price estimation of 3.14 USD/GJ in the baseline scenario is based on the current Indonesia's coal price influenced by the price cap policy of 70 USD/ton (IESR, 2019). Meanwhile, the estimation of coal price, if the price cap policy is annulled i.e. 5.65 USD/GJ, is derived from a rough extrapolation of the average of Indonesia's coal reference price in 2021 i.e. 122 USD/ton (ESDM, 2022). This price is also used in 2030 and 2050 to avoid misestimation in the model because an Indonesian coal price forecast from official data or scientific publications beyond 2030 is not found. Considering that the Indonesian coal price shows a significant fluctuation in the last ten years. For comparison, the price was mostly declining from 127 USD/ton in February 2011 to 51 USD/ton in June 2016. It rose to 107 USD/ton in August 2018 and declined again to 49 USD/ton in September 2020. However, it then kept skyrocketing to its peak at 215 USD/ton in November 2021 (ESDM, 2022d).

3.5.3 Emission-optimum scenario

The emission-optimum scenario is set to explore the optimally minimum level of CO_2 emissions in the 2030 and 2050 systems if the systems do not take into account both the PLN's electricity generation plan and the most-optimum system cost. This scenario has several fundamental differences in the system configuration compared to that of the cost-optimum baseline scenario. First, the electricity generation mix of the 2030 model is not constrained by that of RUPTL PLN 2021-2030. Instead, it is set as a variable with respect to the nominal capacity of each power plant in each region. For the 2050 model, the nominal capacity of fossil fuel power plants is also set to be variable. Second, the capacity factor of all power plants in 2030, as well as 2050, is constrained to be 99% at maximum so as to roughly consider the time used for maintenance. Lastly, these models are run to solve the optimization problem with the objective to minimize the systemwide emission level with regard to demand fulfilment at every timestep.

However, if the technical potential of renewable energy in Kalimantan is significantly larger than the total demand in 2050, the 2050 model will run with the cost-optimum objective because it has the probability to achieve zero emissions without having to set an emission-minimum objective. The capacity of fossil power plants will be set to zero and other configurations mentioned in the previous paragraph remain the same. Thus, if the cost-optimum result from the 2050 model with the aforementioned configurations already achieves zero emissions with fulfilled demand, the emission-optimum scenario for the 2050 model will not be run as the goal of this analysis has been accomplished cost-optimally. Otherwise, the 2050 model will run on the emission minimization objective with regard to demand fulfilment at every timestep.

3.6 Model and result validation

The main results obtained from the optimization are a levelized cost of electricity (LCOE) for both systemwide and each type of power generation, total system costs, total system emissions, and hourly and regionally supply-demand balance. These are validated by evaluating the results with official documents, scientific literatures, and interviews. The baseline 2021 and 2030 models are validated mainly by using RUPTL PLN, PLN Statistics, and other official reports related to ESDM and PLN. The 2050 model is validated by using additional scientific sources and news articles because a number of government plans related to the energy transition are not yet corroborated in policies or regulations.

3.7 Stakeholder interviews

Optimization of the Kalimantan power system using system dynamics modelling is based on numerical data and limited to simplification and assumptions. This results in a lack of a deeper understanding of the actual situation of the real system. Therefore, ten various stakeholders related to the Kalimantan power system are interviewed to gather insights regarding the Kalimantan power system in real life. These stakeholders are selected by several criteria such as occupancy, place of origin, place of residence, residential settings, and energy-related background so that the insights obtained are comprehensive based on different perspectives. In addition, the interview questions are based on their respective occupation. It means that, for instance, residents get different interview questions compared to government officials. Therefore, some interviewees may only provide insights related to one or two energy justice parameters, while the others provide insights related to all energy justice parameters. The list of stakeholders and their selection criteria are presented in **Table 2**. Furthermore, the insights obtained from the interviews are analysed to provide deeper deliberation in the result validation and energy justice analysis.

Table 2 List of interviewed stakeholders

ID	Criteria				
	Occupancy	Place of origin	Place of residence	Residential settings	Background
01	Resident	Kalimantan	Banjarbaru, South Kalimantan	Middle-class suburban	Non-energy
02	Resident	Kalimantan	Balikpapan, East Kalimantan	High-class suburban	Non-energy
03	Resident	Kalimantan	Pontianak, West Kalimantan	Middle-class urban and rural	Non-energy
04	Govt official / resident	Java	South Barito, Central Kalimantan	Suburban govt housing	Electricity service
05	Govt official	Java	-	-	Energy transition
06	Govt official / resident	Java	Kubu Raya, West Kalimantan	Urban govt housing	Non-energy
07	NGO / resident	Kalimantan	Samarinda, East Kalimantan	Middle-class urban	Rural electrification
08	NGO	Java	-	-	Rural electrification
09	Coal mining / resident	Java	South Barito, Central Kalimantan	Rural company housing	Coal expert
10	Coal power plant	Java	-	-	Power plant expert

3.8 Energy justice analysis

The results from the optimization process will be evaluated in terms of energy justice using energy justice as a decision-making tool framework from Sovacool & Dworkin (2015) to provide insights and recommendations regarding power system expansion and planning in Kalimantan. Four elements of energy justice i.e. availability, affordability, intragenerational equity, and intergenerational equity are evaluated based on 2021, 2030, and 2050 Kalimantan power system. The definition of each energy justice parameter and its linkage with the power system modelling terms is presented in **Table 3**.

The analysis of the system's affordability is conducted by evaluating the development of LCOE obtained from the 2021, 2030, and 2050 model optimization with the perception of the actual electricity tariffs regulated by PLN in 2021. It also evaluates how the average minimum salary in Kalimantan may be related to the affordability of electricity services based on the consumer's perception. This is also related to the analysis of intergenerational equity where the changes of the LCOEs between 2021, 2030, and 2050 are evaluated whether the future power system is more or less expensive than the previous ones. Intergenerational equity also evaluates its relationship with the systemwide CO_2 emission level and whether achieving zero emissions in 2050 can be a gain or burden to the system cost compared to that of 2021 and 2030. The analysis of the system's intragenerational equity and availability is conducted by evaluating the impact of the constrained 100% electrification ratio, government-planned transmission system expansion for electricity access, and supply-demand balance between these years as well as the land availability of the integration of renewable energy generations. These also have impacts on the system costs and emissions. Therefore, the four elements of energy justice are strongly interrelated in the evaluation of the optimization of the Kalimantan power system.

Table 3 Definition of each energy justice parameter and its linkage with the power system modelling terms

Energy justice parameters	Definition	Modelling terms	Linkage
Affordability	Stable, equitable electricity prices for all groups of consumers	LCOE	Comparison between the optimum LCOE, BPP, tariffs, and minimum salary
Availability	Security of supply and reliability of the power system	RE technical potential, supply/demand balance (no overload)	RE share in electricity generation mix, supply/demand balance per timestep
Intragenerational equity	Fair access to clean electricity service in the present	Electrification ratio, grid locations, CO_2 emissions	Demand fulfilment based on total population, new energy region for grid interconnection, present CO_2 emission level
Intergenerational equity	Future power systems evaded from the harm of the present power systems	CO_2 emissions, LCOE, investment cost level	Development of CO_2 emission level between years, development of LCOE between years, comparison between present and future investment level

Chapter 4

Optimization of Present and Future Kalimantan Power System

4.1 Conceptual model of the Kalimantan power system

4.1.1 Energy regions and transmission systems

The Kalimantan power system model is conceptualized from the actual power system data provided by the Indonesian government. Based on a georeferenced map in the ESDM Geoportal (ESDM, 2022b), the current Kalimantan power system consists of a number of separated transmission systems as shown in **Figure 2**.

The 150kV transmission system in West Kalimantan province is an independent system named Khatulistiwa. This system is separated from the other Kalimantan provinces but has a 275kV transmission line connection with Sarawak, a Malaysian state on the north-western part of Borneo Island, for importing electricity. While, the Sarawak power system itself has no interconnection with the Sabah power system, another Malaysian state on the north-eastern part of Borneo Island, it plans to commission a transmission interconnection with Sabah by 2023 (Sarawak Energy, 2021). Besides, PLN also has a master plan to establish an interconnection between North Kalimantan and Sabah for electricity export/import activity in the future (PLN, 2022). Nevertheless, the realization of this plan is not yet certainly described in RUPTL PLN 2021-2030. Therefore, only the interconnection between West Kalimantan and Sarawak is conceptualised in the model.

Figure 2 Kalimantan power system in 2021. Green lines and dots represent 150kV transmission lines and substations, dark yellow ones represent 275kV transmission lines and substations (i.e. located in West Kalimantan), and light yellow ones represent 70 kV transmission lines and substations (i.e. located in South Kalimantan). Grey lines represent borders of each Kalimantan province, Malaysia, and Brunei Darussalam (ESDM, 2022b).

There are other smaller transmission systems isolated from the Khatulistiwa system in the eastern and southern parts of West Kalimantan. The largest 150kV transmission system in Kalimantan is the Kalseltengtim system that connects the Central, South, and East Kalimantan. Furthermore, the 150kV transmission system in North Kalimantan province is also not yet connected to the Kalseltengtim system. Besides, numerous off-grid systems exist in Kalimantan, but they are not included in the georeferenced map. Nonetheless, a 150kV transmission system interconnection that connects all Kalimantan provinces is expected to establish in 2023 (PLN, 2021).

The initial conceptual model of the Kalimantan power system consists of 69 substations (150kV) and 463 grid-connected power plants. These data are derived from the ESDM Geoportal. These power plants consist of various types, but they are aggregated by the energy carriers used such as coal, oil (diesel), natural gas, biomass (incl. biogas), hydro, and solar. Other types of power plants such as wind, geothermal, and nuclear are not yet established in 2021 Kalimantan (PLN, 2021). The initial conceptual model is implemented in PyPSA. The model is then simplified using k-means clustering to create 20 centroids that are regarded as energy regions presented in **Figure 3**.

Figure 3 The simplification of the conceptual Kalimantan power system in 2021. Left: the initial conceptual Kalimantan power system. Right: the simplified conceptual Kalimantan power system by k-means clustering.

Figure 4 The location of centroids (green dots) with respect to *kabupaten/kota* borders in Kalimantan (black lines).

The location of centroids is projected on the level-2 administrative region map in Kalimantan using layering features in the ESDM Geoportal as shown in **Figure 4.** Each centroid represents simplified transmission systems, electricity generations, and demands. The energy region is then arbitrarily conceptualized by considering both the level-2 administrative region (*kabupaten/kota*) where each centroid is located and the nearest centroid-less *kabupaten/kota* in the same province. Thus, there are 20 energy regions in the conceptual Kalimantan power system in 2021: six in West Kalimantan, five in Central Kalimantan, three in South Kalimantan, five in East Kalimantan, and one in North Kalimantan. The total electricity demand and generation capacity are derived from the population and the power plants located in each region respectively. This approach is used to obtain an approximation of total electricity demand and generation capacity in each energy region that represents actual regional divisions in the real system.

Considering each transmission link is an aggregation of various numbers of different transmission lines, the characteristics of links between energy regions such as thermal capacity and reactance are simplified based on the copper plate. Thus, there are no power flow constraints in the model. The transmission efficiency in the model is considered 91%. This number is derived from the transmission and distribution losses in Indonesia in 2020 according to ESDM (2021). Furthermore, to avoid being clustered in the Kalimantan energy region by the k-means clustering process, a power generation unit in Malaysia i.e. a large hydropower plant and a transmission link between this unit and West Kalimantan are added manually according to the data from ESDM Geoportal.

Figure 5 The location of centroids (red dots) and transmission links (orange lines) with respect to *kabupaten/kota* borders in Kalimantan (black lines) in the 2030 and 2050 conceptual models.

To conceptualize the 2030 Kalimantan power system, the conceptual power system in 2021 is expanded by adding two new centroids as separated energy regions i.e. one in Putussibau, West Kalimantan and another in Tanjung Selor, North Kalimantan and nine new transmission links that interconnect existing and new energy regions according to the power transmission expansion plan in the RUPTL PLN 2021-2030. The exact coordinates for the new 150kV substations are not yet published. Thus, their locations in the model are arbitrarily determined by the location of an existing PLN office in the respective region. Furthermore, the 2050 Kalimantan power system is conceptualised to be identical to the 2030 counterpart because no additional substations are already planned by PLN to be built in the regions outside the energy regions that exist in the 2030 model. The location of centroids and networks of the 2030 and 2050 conceptual models is shown in **Figure 5.**

Nevertheless, there is a plan to build a 500kV transmission system as a backbone of the Kalimantan power system interconnection within this timespan. However, there are three design alternatives still being considered for this plan according to RUPTL PLN 2021-2030. Moreover, the certain realization year of this 500kV transmission system is not explicitly described in RUPTL PLN 2021-2030. Therefore, the backbone transmission system plan is not considered in the model.

4.1.2 Electricity demand

The hourly electricity demand profile for the Kalimantan power system is not openly available. To compensate for this shortcoming, the hourly demand profile from the Malaysia Grid System Operator (GSO) in 2021 is used as a basis for determining the hourly demand per person. The hourly demand per person is derived by dividing the hourly total demand by the total population of Malaysia in 2021. The pattern of the Malaysian hourly demand in 2021 is presented in **Figure 6**.

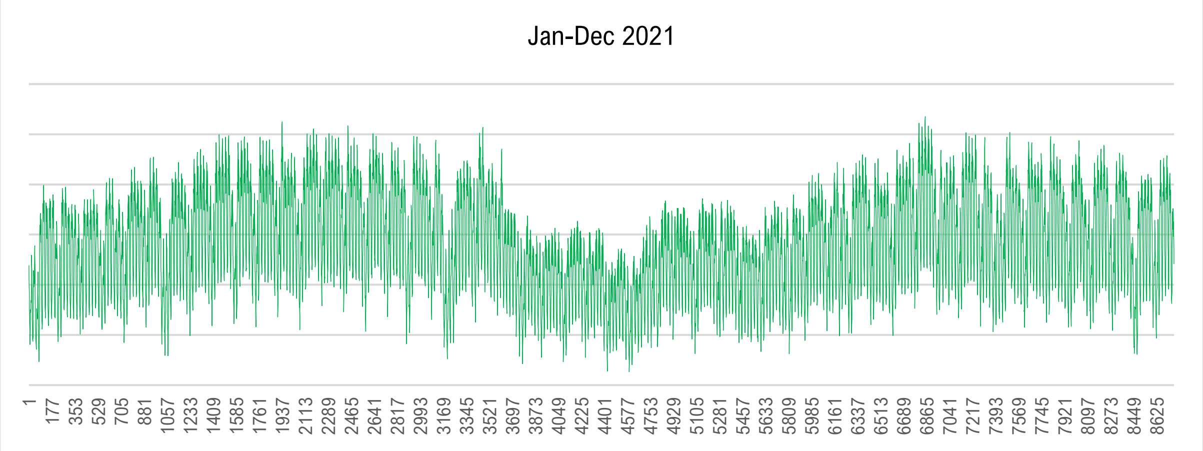

Figure 6 The pattern of the Malaysia hourly demand in 2021.

The electricity demand per person in Kalimantan is derived by dividing the total electricity consumed in Kalimantan in 2021 (PLN, 2022) by the total population of each *kabupaten/kota* in Kalimantan in 2021 (BPS, 2022). Future demand in 2030 and 2050 is conceptualized by multiplying demand per person with a forecasted population in respective *kabupaten/kota* in 2030 and 2045 according to BPS (2018) plus forecasted migrated residents in the new capital city (Salsabila & Nurwati, 2020). The year 2045 is chosen for the 2050 model because Indonesia's population forecast beyond 2045 is not available. Furthermore, the Kalimantan demand per person is extrapolated with the Malaysian hourly demand per person to conceptualize the hourly demand profile of Kalimantan. To determine the hourly demand per energy region, the hourly demand profile per person is multiplied by the population of the energy region. Thus, all energy regions have an identical hourly pattern but a different amount of demand. The division of the Kalimantan energy regions for demand conceptualization is presented in **Figure 7**.

This method has several shortcomings. Firstly, the demand profile might be different in real life due to the less-industrialized and less-urbanized situation of Kalimantan compared to that of Malaysia based on the interviews with ID05. Secondly, demand per person in the future might be different due to technological advancement or electrification in many sectors such as transportation. Meanwhile the actual hourly demand pattern may be different, particularly with regard to peak hours. Thirdly, it is assumed that all Kalimantan residents will be connected to the grid in the future. Lastly, the unelectrified ratio of each Kalimantan province obtained from PLN (2022) is initially considered as the unmet demand in 2021. However, it is not included in the hourly demand due to limited data related to model conceptualization but is discussed further in **Chapter 5**.

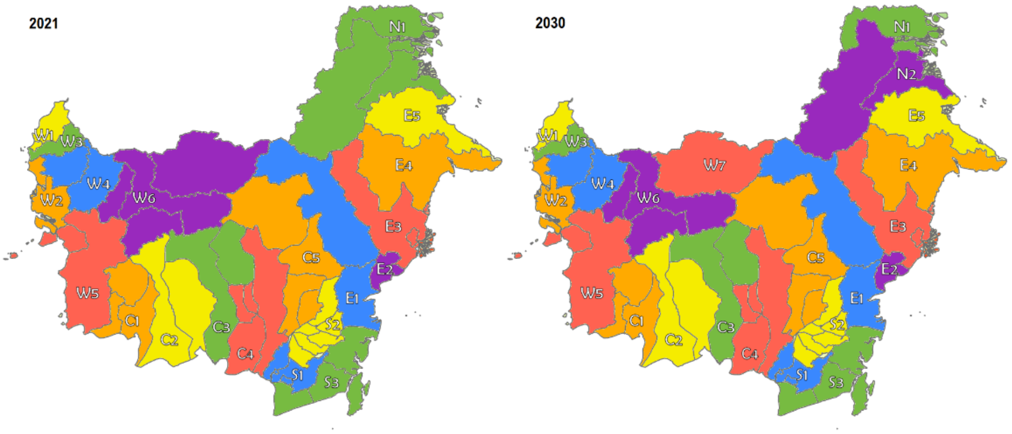

Figure 7 The division of energy regions in the conceptual Kalimantan power system model. The initial in each energy region's name stands for: W = West Kalimantan, C = Central Kalimantan, S = South Kalimantan, E = East Kalimantan, and N = North Kalimantan. Left: energy regions in the 2021 conceptual model. Right: energy regions in the 2030 and 2050 conceptual models. Different colours are used to make borders between each energy region more visible.

4.1.3 Characteristics of power plants and energy storage

The conceptual power plants are aggregated by the types of main energy carriers. Similar types of main energy carriers are distinguished when the spatial characteristic of the technology is significantly different e.g. onshore and offshore wind turbines. Therefore, nine types of power plants are conceptualized in the model i.e. biomass, coal, gas, hydro, nuclear, oil, offshore wind, onshore wind, and solar. In addition, hydropower imported from Malaysia is also conceptualized in the model.

The ocean energy technologies in Kalimantan are not included in the model due to economically suboptimal natural conditions for OTEC in Kalimantan waters (Langer et al., 2021b) and low technical potential for tidal energy in Kalimantan waters (Firdaus et al., 2017). Geothermal is also not included in the model because proven geothermal reserves are yet to be found in Kalimantan (Ahluriza et al., 2021). Kalimantan has one of the lowest geothermal energy potentials in Indonesia i.e. 151 MW of speculative geothermal resources and 13 MW of possible geothermal reserves.

Considering that the capacity of the same type of power plants in the same region is aggregated, the technical and economic characteristics of the types of power generation technologies in the model are aggregated following the types of technologies below:

- Coal : supercritical coal power plants
- Biomass (incl. biogas) : oil palm biomass power plants
- Hydro : reservoir and run-of-river hydro power plants
- Solar : utility-scale solar photovoltaics farms
- Onshore wind : utility-scale onshore wind farms
- Offshore wind : utility-scale offshore wind farms
- Natural gas : combined-cycle gas turbine power plants
- Oil : diesel engine power plants
- Nuclear : light-water nuclear power plants

Furthermore, a cost learning assumption is used in 2030 and 2050 based on forecasted costs from references with Indonesian context. This future cost assumption is based on a one-factor learning curve approach compared to projections from international literatures, with the default learning rate of solar PV is 20% and that of the other technologies is 12.5% (Danish Energy Agency, 2021). In 2050, considering their respective lifetime and commissioning year, most power plants are new power plants that do not yet exist in either 2021 or 2030. All The technical and economic characteristics of each power plant and storage used in the model are presented in **Table 4.** The different economic characteristics of each power plant and storage used in the 2030 and 2050 model are presented in **Table 5.**

Table 4 Technical and economic characteristics of power plants and storage used in the model

Types	Characteristics						Ref.
	Efficiency	CAPEX (M USD/MW)	Fixed OPEX (USD/MWh)	Variable OPEX (k USD/MWh)	CO_2eq emissions (kg/MWh)	Lifespan (yrs)	
Biomass	0.29	2,500,000.00	48,000.00	7.20	0.00	25	*a, b*
Coal	0.38	1,150,000.00	41,200.00	11.30	849.00	30	*a, b*
Gas	0.57	1,920,000.00	23,000.00	24.50	433.00	25	*a, b*
Hydro	0.95	2,290,000.00	41,900.00	0.50	0.00	50	*a, b*
Nuclear*	0.41	-	-	-	0.00	40	*b, c*
Oil/Diesel	0.46	800,000.00	8,000.00	43.90	600.0	25	*a, b*
Offshore wind*	-[#]	-	-	-	0.00	27	*a, b*
Onshore wind	-[#]	1,500,000.00	60,000.00	0.00	0.00	27	*a, b*
Solar	-[#]	1,190,000.00	15,000.00	0.00	0.00	25	*a, b*
Import (hydro)	0.95	2,080,000.00	37,700.00	0.50	0.00	50	*a, b*
Batteries*	0.92	-	-	-	0.00	20	*a, b*

a: Danish Energy Agency (2021)
b: Quaschning (2021)
c: IEA (2020)
**Nuclear, offshore wind, and batteries are included in the 2050 model only*
[#] *Effficency is determined by the simulation results from Renewables.ninja, which may vary across different regions*

Table 5 Economic characteristics of power plants and storage used in the 2030 and 2050 model

Types	2030			2050			Ref.
	CAPEX (M USD/MW)	Fixed OPEX (k USD/MWh)	Variable OPEX (USD/MWh)	CAPEX (M USD/MW)	Fixed OPEX (k USD/MWh)	Variable OPEX (USD/MWh)	
Biomass	2.50	48.00	7.20	1.60	38.10	7.20	*a*
Coal	1.15	41.20	11.30	0.99	38.70	11.30	*a*
Gas	1.92	23.00	24.50	0.61	22.10	24.50	*a*
Hydro	2.29	41.90	0.50	1.85	33.60	0.50	*a*
Nuclear	-	-	-	2.78	15.51	9.33	*c*
Oil/Diesel*	0.80	8.00	43.90	-	-	-	*a*
Offshore wind	-	-	-	2.52	52.30	0.00	*a*
Onshore wind	1.28	51.00	0.00	1.08	43.20	0.00	*a*
Solar	0.56	10.00	0.00	0.41	8.00	0.00	*a*
Batteries	-	-	-	0.36	0.15	1.84	*a*

a: Danish Energy Agency (2021); *c*: IEA (2020)
**Nuclear, offshore wind, and batteries are included in the 2050 model only, while diesel is not included in the 2050 model*

The CO_2eq emissions from biomass combustion are set as zero, assuming that the biomass source is sustainable (Quaschning, 2021). Besides, the variable OPEX of coal power plants takes into account the coal price cap set by the Indonesian government (IESR, 2019). Furthermore, the efficiency of solar PV, on- and off-shore wind is set to be 1.00 in the model input because the solar and wind time series that consider the actual efficiency overrides this number during the simulation.

The energy storage technology considered in the model is utility-scale lithium-ion battery only. Lithium-ion batteries have several advantages such as high energy density, high round trip efficiency, long life span (Kim et al., 2018), and low geographical bound (Luo et al., 2015). It means that a utility-scale lithium-ion battery storage facility can be built at the same sites or nearby the variable renewable energy plants. Meanwhile, although Kalimantan has sufficient PHES site potentials (Blakers et al., 2018), this technology is more geographically bounded and its construction can be more environmentally destructive than that of lithium-ion battery (Moriarty & Honnery, 2016). Moreover, the high-spatial PHES potential sites data in Kalimantan are not yet available. Therefore, considering these shortcomings, PHES is not included in the model.

4.1.4 RE and other clean energy potentials

Five renewable energy technologies are preliminarily considered in the model i.e. solar PV, onshore wind, offshore wind, biomass, and hydro. Considering that most renewable energy technologies are geographically bounded, the generation capacity potentials of these technologies are conceptualized based on spatial constraints where their installations do not conflict with protected areas, natural forests, plantation forests, agricultural lands, airports, seaports, and settlement areas. However, these constraints only apply when sufficient data are available. Therefore, only solar and wind energy potentials include these constraints in a high resolution, while the others are determined from available data with a lower resolution. The preliminary data for the power capacity potential of each technology for the input in the 2050 model is presented in **Table 6**.

Table 6 Preliminary data for the power capacity potential of renewable energy in each Kalimantan province as the modelling input

Types	Power capacity potential (MW)					Ref.
	West Kalimantan	Central Kalimantan	South Kalimantan	East Kalimantan	North Kalimantan	
Biomass	1,308.00	1,499.00	1,290.00	964.00	0.00	*d, e*
Hydro	4,737.00	16,844.00			21,580.00	*f*
Offshore wind	18,290.00	20,830.00	10,840.00	220.00	0.00	*g*
Onshore wind	1,010.00	1,180.00	280.00	60.00	0.00	*g*
Solar	1,577,000.00	1,025,000.00	275,000.00	1,686,000.00	165,000.00	*h*

d: Adistia et al. (2021); *e*: IESR (2019); *f*: ESDM (2019); *g*: Simanjuntak (2021); *h*: Pragt (2021)

4.1.4.1 **Biomass**

Indonesia produces approx. 146.7 million kilograms of biomass waste annually. In Kalimantan, the solid biomass waste comes from oil palm oil residues, rubber wood, logging residues, sawn timber residues, plywood & veneer production residues, sugar residues, and rice residues (Dani & Wibawa, 2018). In terms of power generation potentials, there is great variability between the Kalimantan provinces. East Kalimantan and North Kalimantan have no significant biomass power generation potentials. Its primary reason is not available in references. Meanwhile, Central Kalimantan has the largest potential i.e. 1,499 MW, followed by 1,308 MW and 1,290 MW in West Kalimantan and South Kalimantan, respectively (Adistia et al., 2020). Nevertheless, a higher spatial resolution of biomass power generation potentials is not available.

4.1.4.2 **Hydro**

With high rainfall intensity throughout the year, Indonesia has an enormous hydropower potential for either run-of-river or reservoir. ESDM estimates that Indonesia has a total hydropower potential of 75,091 MW. In terms of Kalimantan, the potential in West Kalimantan is 4,737 MW and the potential in the East Kalimantan, Central Kalimantan, and South Kalimantan are aggregated to be 16,844 MW (ESDM, 2020). In addition, the potential in North Kalimantan is 21,580 MW (ESDM, 2019). Based on the global map of gross hydropower potential distribution, the largest potential is also roughly located in North Kalimantan (Hoes, 2017).

Nonetheless, taking constraints such as protected areas, tourism zones, reservoir size, and resettlement of residents, the practical potential of large hydropower in entire Indonesia is significantly smaller i.e. approx. 26,000 MW (Koei, 2011). Moreover, considering there is no further explanation found related to the aggregation of hydropower potentials in three Kalimantan provinces, the maximum nominal capacity of hydropower in these provinces is only based on the capacity planned per province by PLN and ESDM to avoid mistakes in determining the exact division of this hydropower potential per each of these three provinces.

4.1.4.3 **Wind**

Wind energy has never been contributing to a significant share of energy generation in Indonesia. This shortcoming is apparent as Indonesia only began to have its first large-scale wind farm (75 MW) in 2018 and was followed by the second one (72 MW) in 2019, both located on Sulawesi island. No other large-scale wind energy capacity was added until 2020. One of the main reasons is that wind resources in Indonesia are considered to be relatively scarce and sparse (NEC, 2017). In contrast, the most recent scientific publications indicate that Indonesia has considerable wind energy potential, either offshore or onshore (Simanjuntak, 2021).

Taking seabed depth and artisanal fishing areas into account, the nominal offshore wind power capacity potential in Indonesia is ranging from 2,789.5–3,636.0 GW. Meanwhile, the nominal onshore wind power capacity potential is around 101.9 GW. In Kalimantan, Central Kalimantan has the largest potential for either offshore or onshore i.e. 20,830.00 MW and 1,180 MW, respectively. It is followed by West Kalimantan, South Kalimantan, and East Kalimantan i.e. 18,290 MW, 10,840 MW, and 22 MW for offshore and 1,010 MW, 280 MW, and 60 MW for onshore, respectively. Meanwhile, North Kalimantan has zero potential for both onshore and offshore wind energy (Simanjuntak, 2021). The spatial distribution of the potential sites for offshore and onshore wind energy in Kalimantan is presented in **Figure 8**.

The spatial distribution maps in **Figure 8** are used to determine which energy region in the model has wind power generation capacity potentials for the 2050 model. Furthermore, it is also used to determine the specific location of wind turbines to simulate the hourly wind generation profile using Renewables.ninja simulation. East Kalimantan is considered to have zero potential in the 2050 model as it has an insignificant amount of potential. Thus, the maximum wind power nominal capacity in each province in the 2050 models is constrained by the data from Simanjuntak (2021), unless there is a larger generation capacity planned by RUPTL PLN 2021-2030.

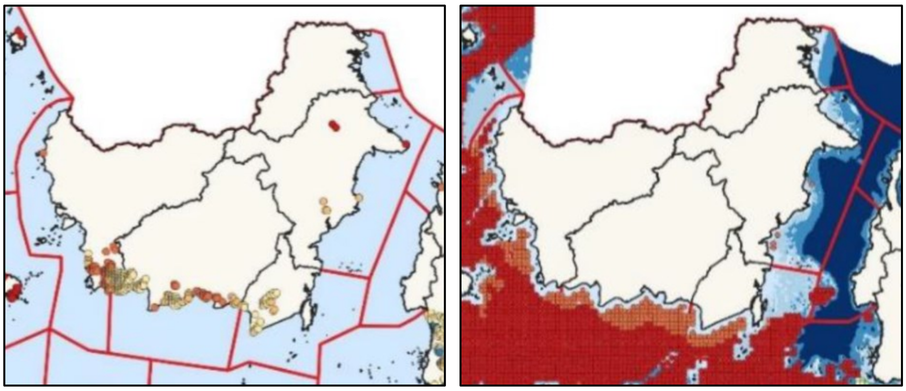

Figure 8 Spatial distribution of potential sites (coloured dots) of wind power production in Kalimantan with variability in economic feasibility according to Simanjuntak (2021). This variability of economic feasibility is not taken into account in the model because the model uses a lower spatial resolution. Left: onshore wind energy, with economic feasibility of area with green dots > yellow > orange > red. Right: offshore wind energy, with economic feasibility of area with orange > red.

Based on the spatial distribution, five points in each energy region with wind power generation potential are chosen. The points are roughly determined by comparing the dots from Simanjuntak (2021) and the spatial distribution of mean wind speed on the Global Wind Atlas. These points are then used for obtaining the energy per capacity (MWh/MW) time series dataset using Renewables.ninja simulation. The year 2020 is used in that simulation because the years after are not yet available. The average energy per capacity from five points is used for respected energy regions in 2021, 2030, and 2050 models. The onshore and offshore wind energy per capacity time series graph in region S3 are presented in **Figure 9**.

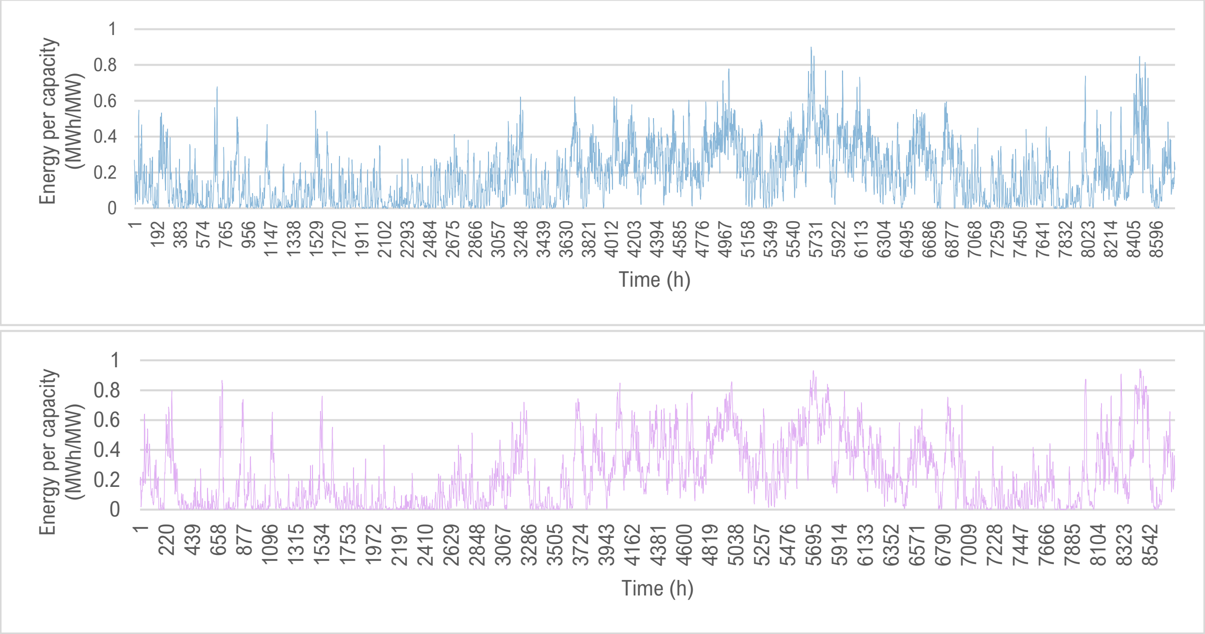

Figure 9 Averaged wind energy per capacity timeseries graph in region S1 (top, onshore) and S3 (bottom, offshore) used in the model.

4.1.4.4 **Solar**

Indonesia is estimated to have around 153 thousand square kilometres of suitable areas or 6,310 GWp of potential solar PV power. This estimation is constrained by the ground slope limit (10°) and exclusion areas such as protected areas, forests, water bodies, wetlands, agricultural lands, airports, seaports, and settlement areas (IESR, 2021). Furthermore, the potential of rooftop solar PV is not considered in the model because determining the potential number of rooftop PV installations in future Kalimantan is out of scope.

In Kalimantan, East Kalimantan has the largest potential for solar PV power capacity i.e. 1,686 GWp. It is followed by West Kalimantan (1,577 GWp), Central Kalimantan (1,025 GWp), South Kalimantan (275 GWp), and North Kalimantan (165 GWp). These power capacity potentials are enormously larger than the total electricity demand during the daytime in Kalimantan. This data also already excludes several potential drawbacks such as land acquisition difficulties, more restrictive land use, and economic potential. The spatial distribution map is used to determine which parts of the energy region in the model have significant solar power capacity potentials for the 2050 model. The suitable areas are mapped based on the aforementioned geographical constraints (Pragt, 2021). The spatial distribution of suitable areas for solar PV in Kalimantan based on geographical constraints is presented in **Figure 10**.

Based on the spatial distribution, five points in each energy region with suitable solar power generation areas are chosen. The points are roughly determined by comparing the suitable areas from Pragt (2021) and the spatial distribution of mean specific photovoltaic output on the Global Solar Atlas. These points are then used for obtaining the energy per capacity (MWh/MWp) time series dataset using Renewables.ninja simulation. The year 2020 is used in that simulation because the subsequent years are not yet available. The average energy per capacity from five points is used for the respected energy region in the 2030 and 2050 models. The 2021 model uses a single point for each existing solar PV farm because the exact coordinates are known. The solar energy per capacity time series graph in region E5 are presented in **Figure 11.**

Figure 10 Spatial distribution of suitable areas (green shades) for solar PV in Kalimantan based on geographical constraints according to Pragt (2021).

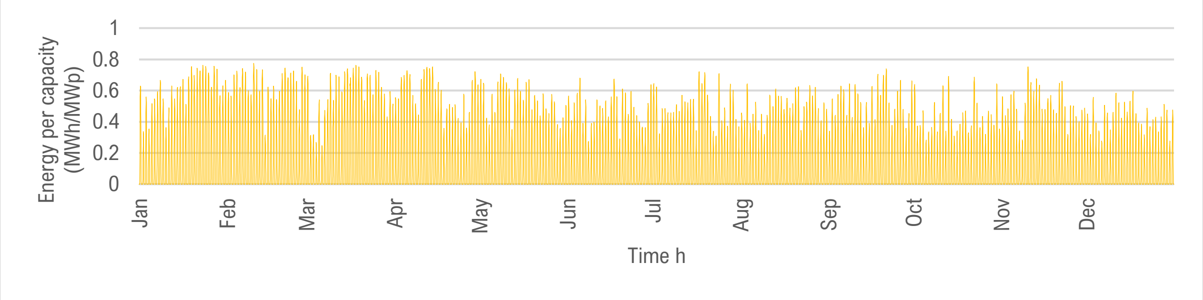

Figure 11 Averaged solar energy per capacity timeseries graph in region E5

4.1.4.5 **Hydro (import)**

West Kalimantan imports electricity from a company named SESCO in Malaysia. Electricity import from Malaysia is considered renewable energy because it is generated from a large hydropower plant (PLN, 2021). The power capacity imported via this transmission is 100-120 MW (Wicaksono, 2017), with a maximum capacity of 170 MW (PLN, 2021). This electricity is transmitted via a 90km high-voltage line to a 275kV substation in Bengkayang, West Kalimantan. The voltage is then reduced to 150kV to be transmitted to the Khatulistiwa system (Wicaksono, 2017). In the model, the electricity import is constrained by the electricity import plan published in RUPTL PLN 2021-2030. According to RUPTL PLN 2021-2030, electricity import in the Kalimantan electricity mix in 2030 is estimated to be zero. Thus, it is set to be zero in the 2030 and 2050 models.

4.1.4.6 **Nuclear**

Nuclear energy is non-renewable, but it can contribute to reduce GHG emissions in future clean energy systems (IEA, 2020). Virtually, nuclear power plants produce no GHG or air pollutants during their operation and low emissions over their full life cycle (IAEA, 2020). Nevertheless, these claims are not socially sound as nuclear power necessarily creates difficulties in the management of nuclear waste and poses a risk of serious accident and social issues (Huang & Chen, 2021). Moreover, newer nuclear technologies do not yet solve these critical problems (Guidolin & Guseo, 2016).

Indonesia still has no nuclear power capacity as of 2021 and the addition of nuclear power capacity is not considered anywhere in RUPTL PLN 2021-2030. However, the National Research and Innovation

Agency of Indonesia (BRIN) mentions a government plan to build a 1.4 GW nuclear power plant in Bengkayang, West Kalimantan in the future, although without mentioning the commissioning year (Pahlevi, 2021). The nuclear power plant development in West Kalimantan is potential due to its stable geological condition and low risk of an earthquake (Setiawan, 2022). Feasibility studies for a nuclear power plant in West Kalimantan have been undergoing by ESDM (Hamdani, 2022). Furthermore, BRIN also claims a survey in 2019 shows that 87% of local residents support this plan (Setiawan, 2022). Considering this recent information, a variable input from zero to a maximum of 1,400 MW of nuclear power capacity is included in region W3 in the 2050 model.

4.1.4.7 Lithium-ion battery

Lithium-ion batteries have gone to play an important role in the reduction of the world's GHG as it is becoming the technology of choice for different energy storage solutions (Melin, 2019). It has experienced considerable cost declines in the past few years. Its potential applications in power systems are broad, ranging from supporting weak distribution grids to the provision of bulk energy services and off-grid solutions (Danish Energy Agency, 2021). Moreover, its operation is virtually emission-free, although the emissions from its full life cycle can be considerable (Melin, 2019).

As of 2021, Indonesia still has zero deployments of utility-scale lithium-ion battery storage (PLN, 2021). Its deployment is also not considered in RUPTL PLN 2021-2030. Therefore, also considering its low geographical constraints and rapid development in recent years, the maximum capacity of lithium-ion battery storage is set to be infinity in the 2050 model so that the model algorithm determines the most cost-optimum capacity needed in the system.

4.2 Validation

4.2.1 Time resolution

The 2021 model is able run properly in an hourly time resolution. However, some errors occurred when running the 2030 and 2050 models in an hourly time resolution, despite no error occurs if the runs are separated per month. The errors might occur due to the increased complexity of the constraints for economic dispatch optimization in the 2030 and 2050 models. Therefore, the 2-hourly time resolution is used to run the optimization process without any errors for all scenarios.

The 2-hourly time resolution model is validated by comparing its result with the result from the hourly time resolution model. Both results show identical output in terms of capacity factor (CF) and levelized cost of electricity (LCOE) of each type of generator. Therefore, the assessment of the results from 2-hourly resolution models can be considered similar to that of the hourly resolution models. The result comparison between hourly and 2-hourly resolution in the 2021 model is presented in **Table 7.**

Table 7 Comparison of results between hourly and 2-hourly resolution in the 2021 model

Type	CF		LCOE (USD/MWh)	
	hourly	2-hourly	hourly	2-hourly
Biomass	0.54	0.54	75.83	75.83
Coal	0.41	0.41	59.66	59.66
Diesel	0.08	0.08	180.60	180.53
Gas	0.43	0.43	82.05	81.69
Hydro	0.85	0.85	20.43	20.43
Import	0.60	0.60	25.90	25.90
Solar	0.16	0.16	67.45	67.45

4.2.2 Electricity generation mix in 2021 and 2030

The maximum share of demand fulfilment of each type of power generator is constrained to approximately emulate the actual electricity generation mix in the Kalimantan power system in 2021. The actual electricity generation mix in 2021 is obtained from RUPTL PLN 2021-2030. To validate the 2021 cost-optimum baseline model, the electricity generation mix result is compared with that of RUPTL PLN 2021-2030. Furthermore, because RUPTL also describes the planned electricity generation mix in 2030, the electricity generation mix of the 2030 cost-optimum baseline model is also validated using the same method as shown in **Figure 12**.

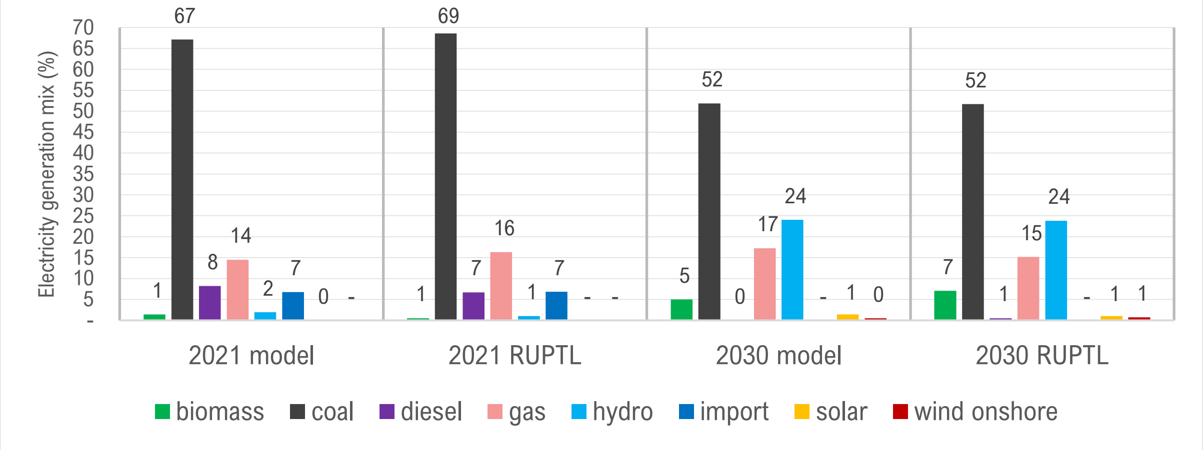

Figure 12 Kalimantan's electricity generation mix in 2021. Left: modelling result. Right: RUPTL PLN.

The largest difference between the 2021 model and RUPTL is in the share of gas i.e. 1.82%. Meanwhile, the solar PV generation in RUPTL PLN is stated as 0.00%, although based on ESDM Geoportal, there is a total solar PV nominal capacity of 1.22 MW in Kalimantan in 2021. This zero share of solar in RUPTL PLN might result from a solar electricity generation of less than 0.00% in the real system. It might be not captured by the published two-decimal data because the sum of that of RUPTL PLN is only 99.99%. Moreover, the electricity generation mix of electricity import in the 2021 model is validated as it generates on average 102.87 MW of energy transmitted to region W3, with the actual import in 2021 being 111.04 MW (ESDM, 2022). It also means that the total demand conceptualized in the model is validated as the amount of the electricity imported can emulate a comparable amount of its electricity consumption in the real system. Overall, the other types of power generators have less than a 1.5% difference between that of the modelling result and RUPTL PLN.

4.2.3 LCOE of each type of power plants in 2021

Table 8 Comparison of the LCOE of each type of power plants in the 2021 model

Type	LCOE (USD/MWh)		Ref.
	2021 model	Reference	
Biomass	75.83	46.80—114.00	(IESR, 2019a)
Coal	59.66	57.70—80.50	(IESR, 2019a)
Diesel	180.60	104.00—615.00	(IESR, 2019a)
Gas	82.05	66.90—89.30	(IESR, 2019a)
Hydro	20.43	19.00—85.00	(ASEAN, 2016)
Import (hydro)	25.90	19.00—85.00	(ASEAN, 2016)
Solar	67.45	58.40—102.80	(IESR, 2019a)
Wind onshore	-	73.90—161.00	(IESR, 2019a)

The LCOE of each type of power plant from the 2021 modelling results is comparable to that of the reference based on the Indonesian context. This comparison is used to validate the equivalence of the electricity price based on the system costs. Considering that the actual margin between electricity prices and costs in Indonesia is not openly available. The comparison of the LCOE of each type of power plant in the 2021 model is presented in **Table 8**.

4.3 Optimization results

4.3.1 Baseline: Cost-optimum economic dispatch

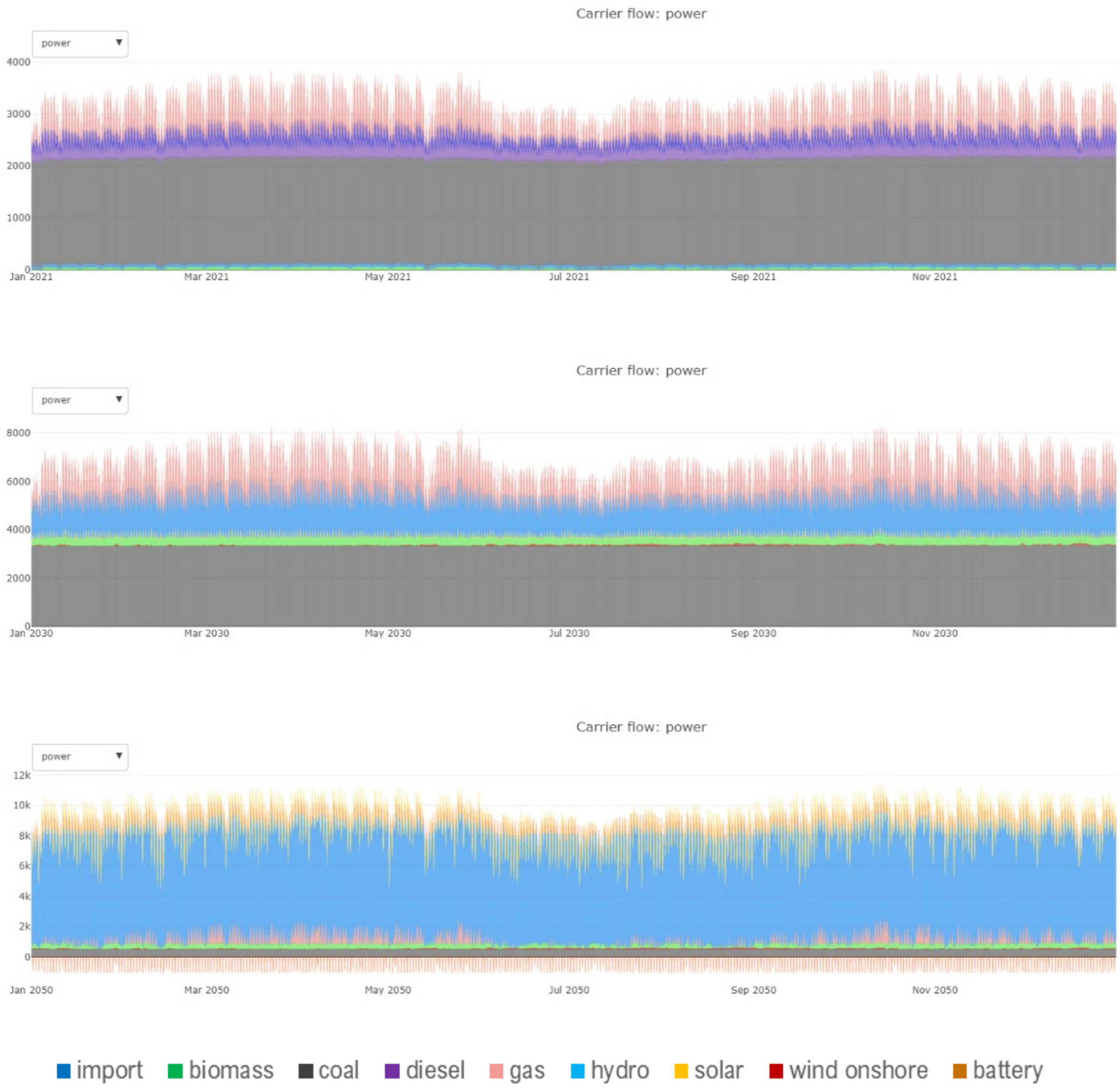

Figure 13 Economic dispatch cost optimization result for the entire year of each model. X-axis = time in 2-hour and Y-axis = MW. Each colour represents different types of power plants. Top: 2021 model. Middle: 2030 model. Bottom: 2050 model.

The results of the economic dispatch optimization of each year show observable patterns of each type of power plant. Coal dispatches the largest share of baseload in 2021 and 2030 since the models are constrained by the actual and planned shares from RUPTL PLN. In contrast, a combination of hydro, solar, and biomass dispatches a much larger share than coal for baseload in 2050 because its maximum potential capacity exceeds the remaining nominal capacity of coal. In addition, hydro as well as gas act as load-following and peaking power plants. Furthermore, variable RE such as solar dispatches whenever they produce electricity, during either off-peak or peak demand. The excess electricity from variable RE is stored in batteries, which feed the electricity back to the grid when needed. The other types of power plants included in the input configuration such as nuclear and offshore wind are not selected by the 2050 cost-optimization. The economic dispatch optimization results from the baseline scenario are presented in **Figure 13**.

Taking a closer look into a week period as presented in **Figure 14**, similar patterns can be observed between the system with a low share of variable renewable energy (2021 and 2030) and the high share counterpart (2050). In 2021 and 2030 where coal accounts for more than half of the hourly electricity generation, the pattern of electricity supply matches the demand in every timestep. Considering that even in 2030, the share of solar electricity generation is still smaller than 1.5%, resulting in insignificant excess electricity when solar energy is available. In contrast in 2050 when solar energy has a significantly higher share in the mix, solar electricity generation considerably exceeds the demand in the timesteps when solar energy is available. However, the excess electricity does not become an issue as it is directly stored in the batteries at the same timestep.

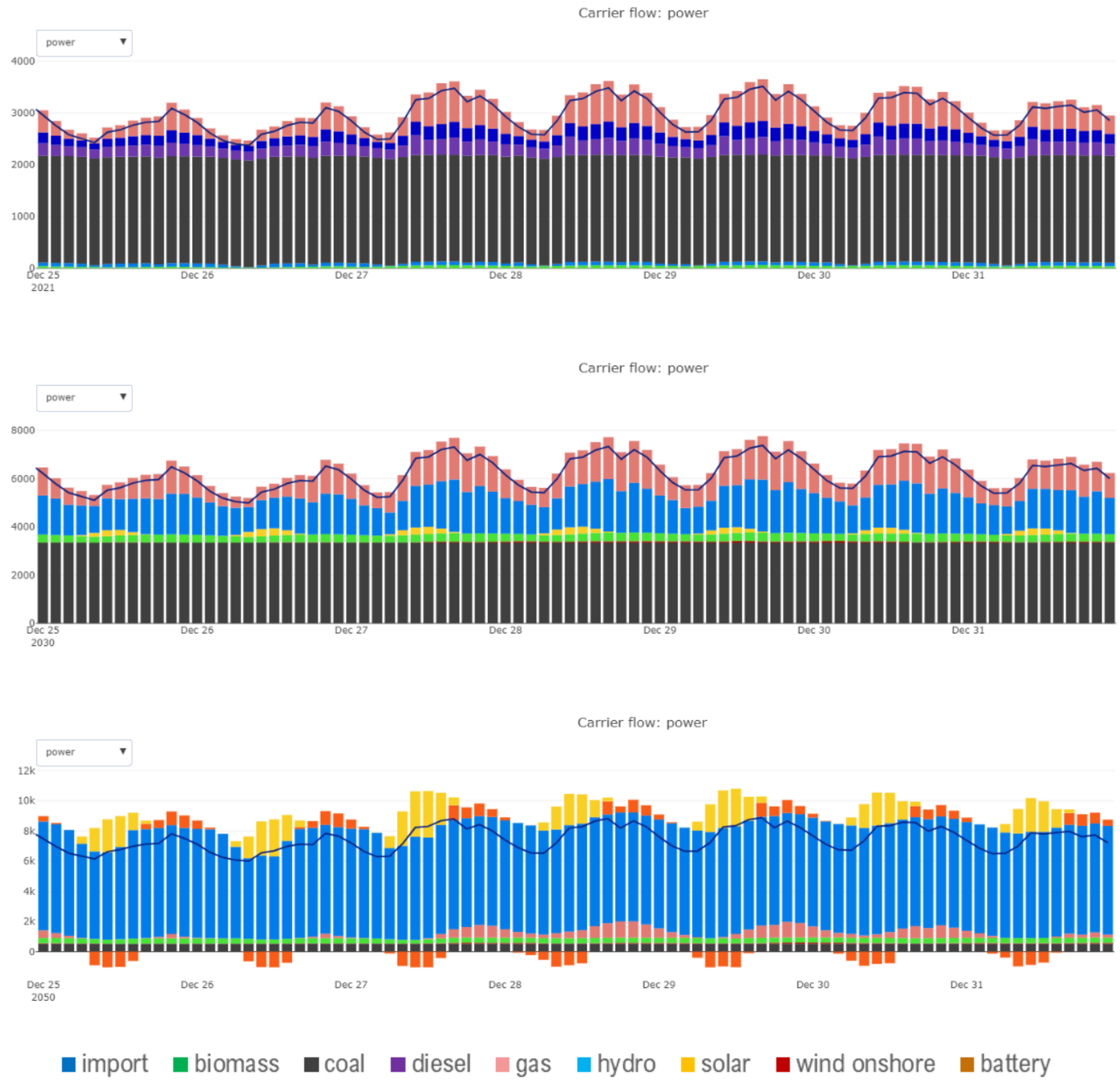

Figure 14 Electricity generation pattern in a week. Dark blue lines represent demand. X-axis = time in 2-hour and Y-axis = MW. Sample period is Dec 25-31. Top: 2021 model. Middle: 2030 model. Bottom: 2050 model.

The absence of solar during peak hours in the evening is well-managed by batteries and gas in order to balance the load. Right after the solar energy is not available anymore, the batteries feed the stored electricity back to the grid during the remaining peak hours. This is better be done because batteries are self-discharging at a certain rate, although it is not significant in a short-term period. Furthermore, the other reasons for sufficient load balancing in the 2050 model are that the availability of solar in Kalimantan throughout the year is relatively less intermittent.

The nominal power capacity of each type of power plant systemwide demonstrates the reliance on fossil fuels in the current Kalimantan power system as shown in **Figure 15**. The nominal capacity of fossil fuels accounts for enormously 94.87% of the total installed capacity in 2021. Furthermore, considering new power plant planning in RUPTL PLN 2021-2030 and phasing out power plants that surpass their theoretical lifetime, it still accounts for more than half of the total installed capacity in 2030, i.e. 67.57%. However, based on the model cost-optimization, it is significantly reduced to only 12.33% in 2050, assuming no additional fossil fuel power plants are installed from 2031 to 2050. It means the future state of the Kalimantan power system is immensely uncertain, depending on whether new fossil power plants are still considered in the future capacity planning or not.

On the other hand, the development of renewable power capacity focuses intensely on hydro, solar, and biomass power plants. Based on RUPTL PLN 2021-2030, the nominal capacity of hydropower is massively expanded from 34.51 MW in 2021 to 1,217.48 MW in 2030. Meanwhile, that of solar, biomass, and onshore wind is expanded from 1.22, 41.11, and 0.00 MW in 2021 to 307.00, 221.71, and 70.00 MW in 2030, respectively. Furthermore, that of hydro is almost tripled to 3604.81 MW in 2050 based on the model cost-optimization, while that of solar is expanded more than eight-fold to 2644.08 MW. However, the nominal capacity of biomass and onshore wind is slightly reduced to 173.50 MW and 60.82 MW, respectively. A total of 518.26 MW lithium-ion battery storage is installed to support the deployment of solar PV in 2050. In contrast, other clean technologies i.e. offshore wind and nuclear are not included in the cost-optimum configuration due to their relatively more expensive costs.

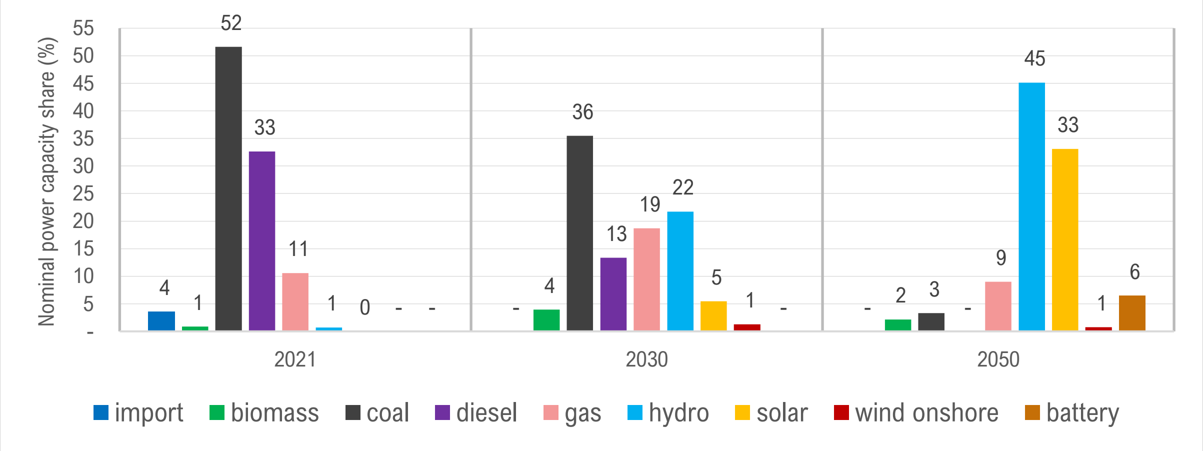

Figure 15 Comparison of systemwide nominal power capacity share (in %) of each type of power plant from each modelling year.

The electricity generation mix from the 2021 and 2030 model optimizations is approximately predetermined based on the actual and planned electricity generation mix in Kalimantan by PLN. In contrast, the electricity generation mix in the 2050 model is generated solely based on the cost-optimization of the parameters and constraints configured in the model. The electricity generation mix shows the possibility of phasing out coal power plants gradually in the future. The electricity generation mix of all cost-optimized models is presented in **Figure 16**.

The reliance on coal for baseload can be replaced by hydro, solar, biomass, and onshore wind power plants in the system. The deployment of lithium-ion battery storage by 2.87% in the mix is cost-optimum to support the variability of 9.26% solar in the mix. Furthermore, diesel generators are significantly diminished by 2030 and completely phased out from the system by 2050. The optimization result shows only a 0.001% share of diesel in the 2030 electricity mix, while PLN plans to have a mere 0.50% share of diesel in the same period (PLN, 2021). It means that phasing out diesel generators in Kalimantan is a cost-optimum plan.

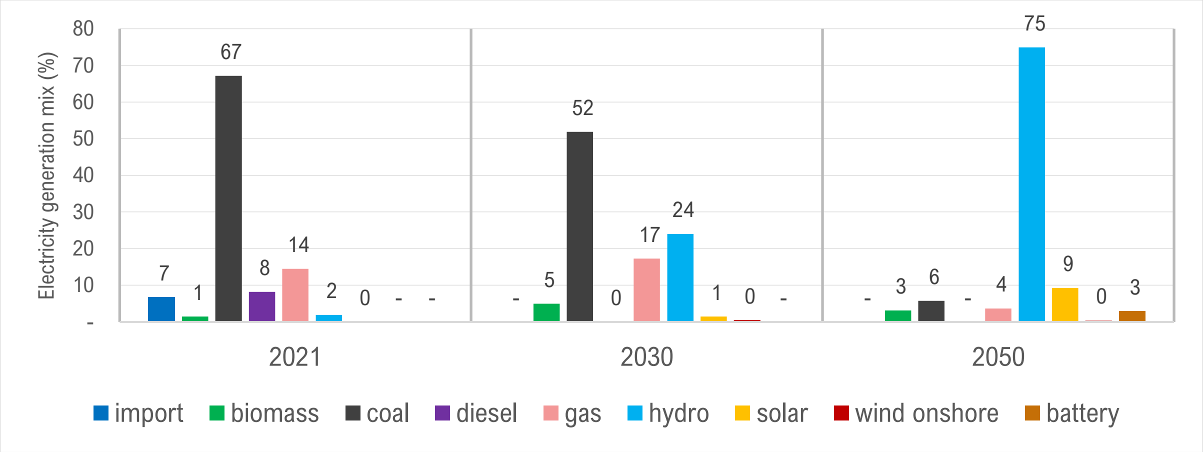

Figure 16 Comparison of the electricity generation mix (in %) from each modelling year based on cost-optimization.

4.3.2 Coal price cap annulment

The cost-optimization of the scenario where the coal price cap is annulled shows reasonable shifts in coal electricity generations. When the fuel cost of coal power plants is increased to be the same as the average global coal price, the share of coal in the electricity generation mix is reduced in all modelling years. In 2021, due to the limited capacity of renewable energy, the gas electricity generation increases from 14.48% to 19.32% to cost-optimally substitute the reduced coal electricity generation. On the other hand, that of the others remains the same. It should be noticed that coal in the 2021 result has a capacity factor of only 41% and 38% in baseline and coal price cap annulment scenarios, respectively, due to overcapacity. The overcapacity of coal happens due to PLN's demand growth overestimation in the past (Hamdi & Adiguna, 2021).

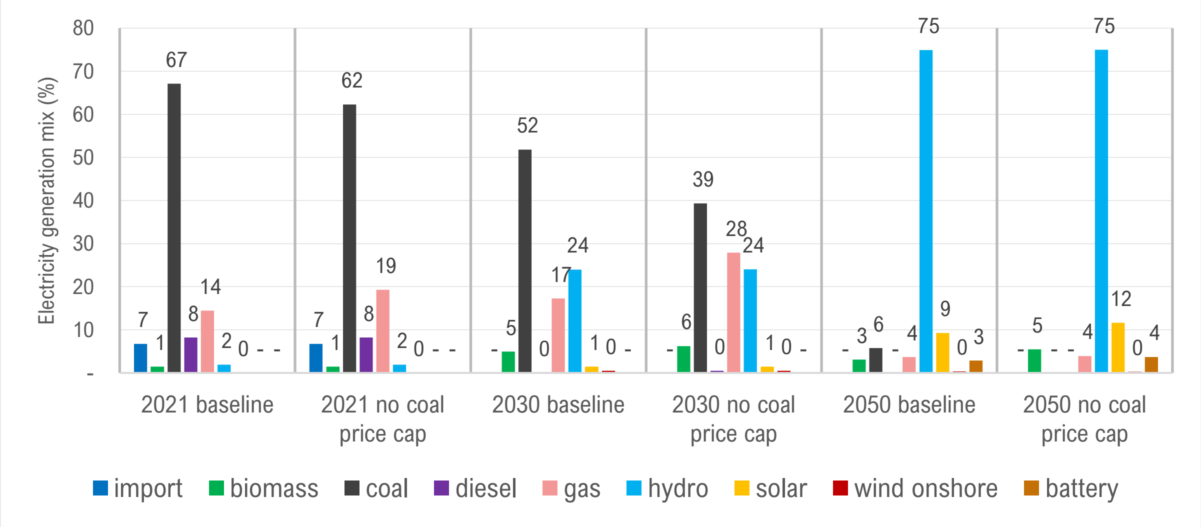

Figure 17 Cost-optimum electricity generation mix difference due to coal price cap annulment.

In contrast, the electricity generation mix in 2030 and 2050 differs significantly between the baseline and coal price cap annulment scenarios. The share of coal in the 2030 mix is reduced significantly from 51.84% to 39.35%, being replaced mostly by gas and biomass. Meanwhile, the share of coal in 2050 is completely gone and replaced mostly by biomass, solar, and batteries. These results show that the coal price cap policy might hinder the development of RE such as biomass and solar in Kalimantan, while the annulment of this policy in the future can potentially boost the development of these renewables. The differences in the electricity generation mix of all modelling years due to coal price cap annulment are presented in **Figure 17**.

4.3.3 Emission-optimum economic dispatch

The electricity generation mix comparison of both emission- and cost-optimized models in 2030 and 2050 are presented in **Figure 18.** The 2030 economic dispatch of both emission- and cost-optimizations are presented in **Figure 19**. The result of the emission-optimum 2030 shows a pattern where the load-balancing is similar to that of the cost-optimum counterpart but with different shares of types of electricity generation. A significant portion of coal electricity generation for baseload is replaced mostly by hydro, biomass, and gas. Moreover, to compensate for a large increase of gas for baseload that reduces their role for peak demand, a reasonable increase of diesel is dispatched during peak hours. Gas and diesel are preferred over coal because they have lower theoretical CO_2eq emissions. However, diesel is no longer favoured in the real-life system by 2030 due to its lower efficiency compared to steam engine counterparts (e.g. coal and gas) which leads to higher costs. Meanwhile, the generation of solar and wind mostly remains the same due to their limited available capacity.

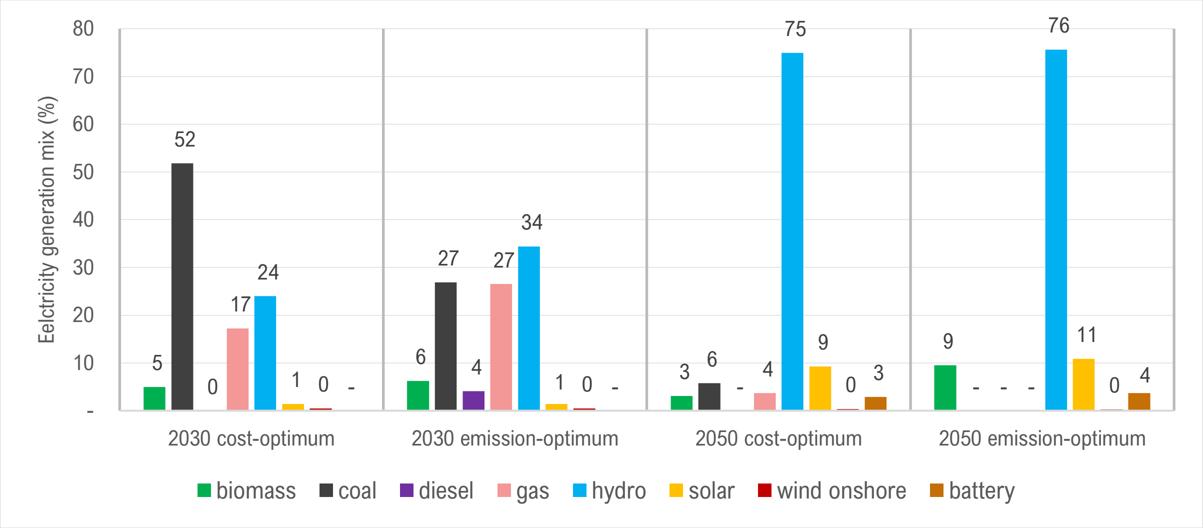

Figure 18 Comparison of the electricity generation mix between cost-optimum and emission-optimum in 2030 and 2050.

The result of the 2050 emission-optimum scenario shows a remarkable different pattern between cost-optimized and emission-optimized systems. The 2050 economic dispatch of both emission- and cost-optimizations are presented in **Figure 20**. Due to the enormous potential of RE capacity in the system, particularly dispatchable RE, coal and gas generation can be completely replaced by mostly hydro with the support of biomass, solar, onshore wind, and batteries in 2050. Hydro works as both baseload and peaking power plants. However, the variability of solar creates a considerable fluctuation in baseload, particularly during daytime when solar energy is available. A deployment of utility-scale batteries becomes indispensable to store the excess electricity from solar and feed the stored electricity back to the grid when needed. Moreover, a tiny capacity of intermittent onshore wind does not create a significant fluctuation from the systemwide perspective.

Figure 19 Economic dispatch optimization results for 2030. X-axis = time in 2-hour and Y-axis = MW. Each colour represents different types of power plants. Top: emission-optimized result. Bottom: cost-optimized result.

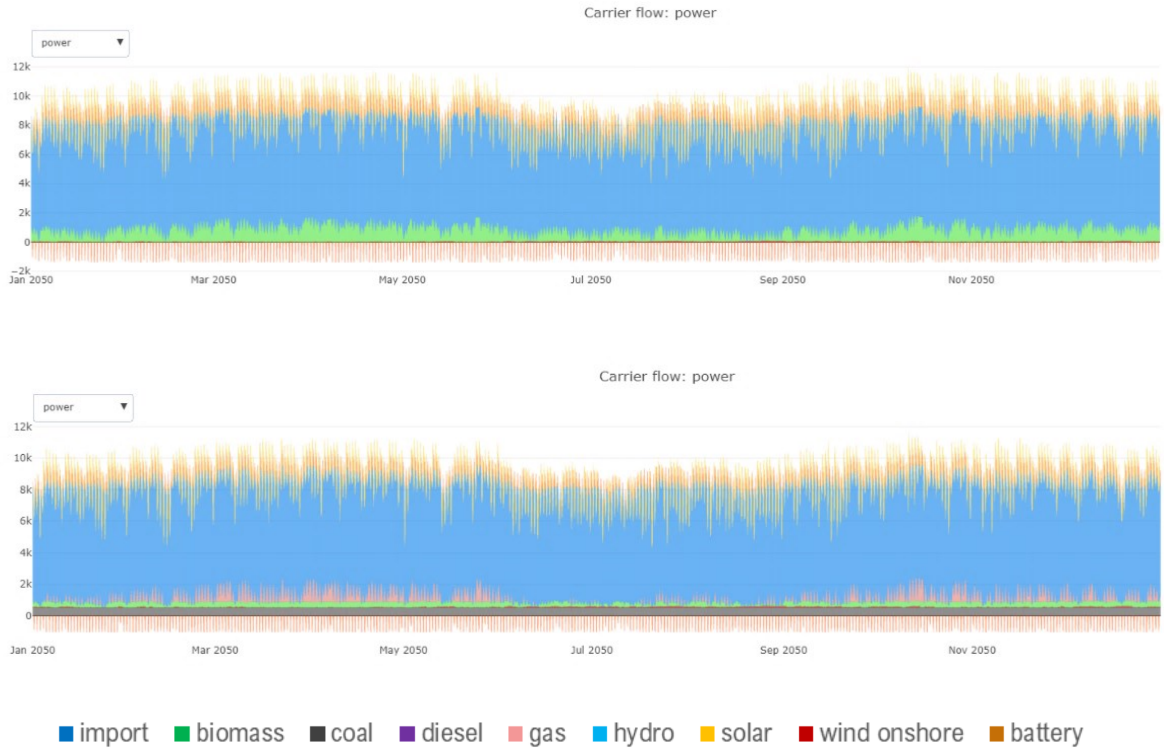

Figure 20 Economic dispatch optimization results for 2050. X-axis = time in 2-hour and Y-axis = MW. Each colour represents different types of power plants. Top: emission-optimized result. Bottom: cost-optimized result.

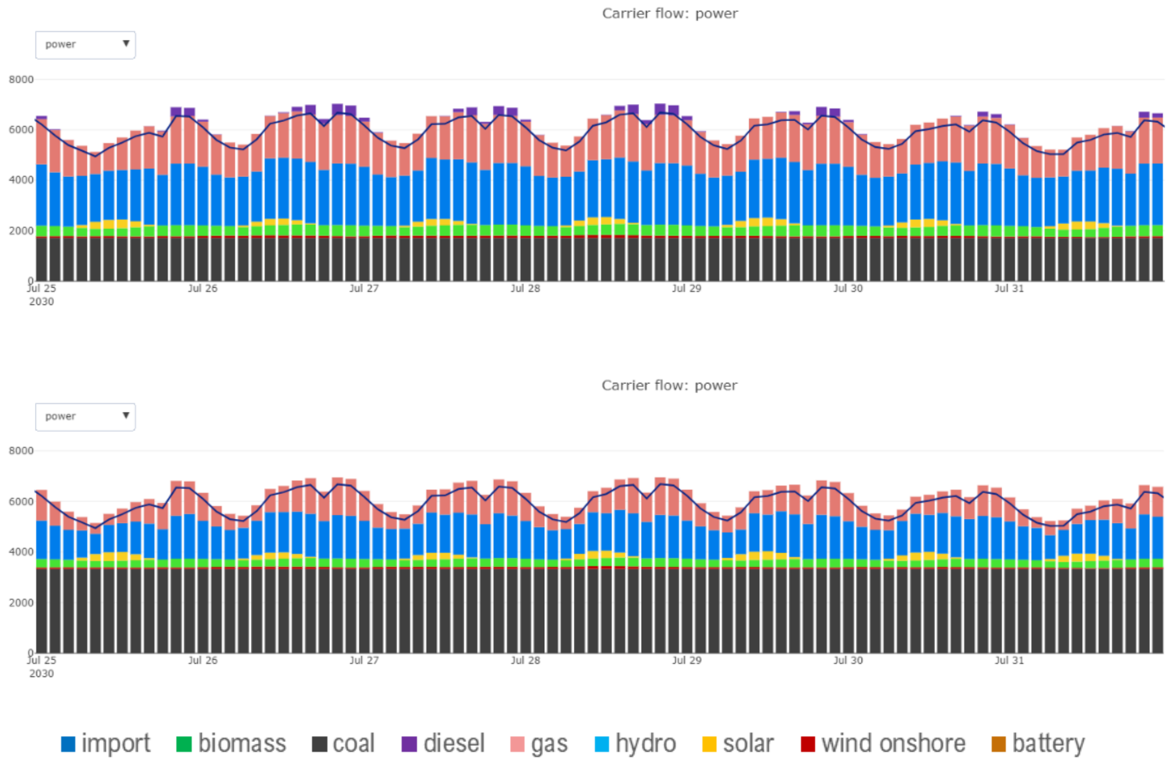

Figure 21 Comparison of the 2030 electricity generation pattern in a week. Dark blue lines represent demand. X-axis = time in 2-hour and Y-axis = MW. Sample period is Jul 25-31. Top: emission-optimization result. Bottom: cost-optimization result.

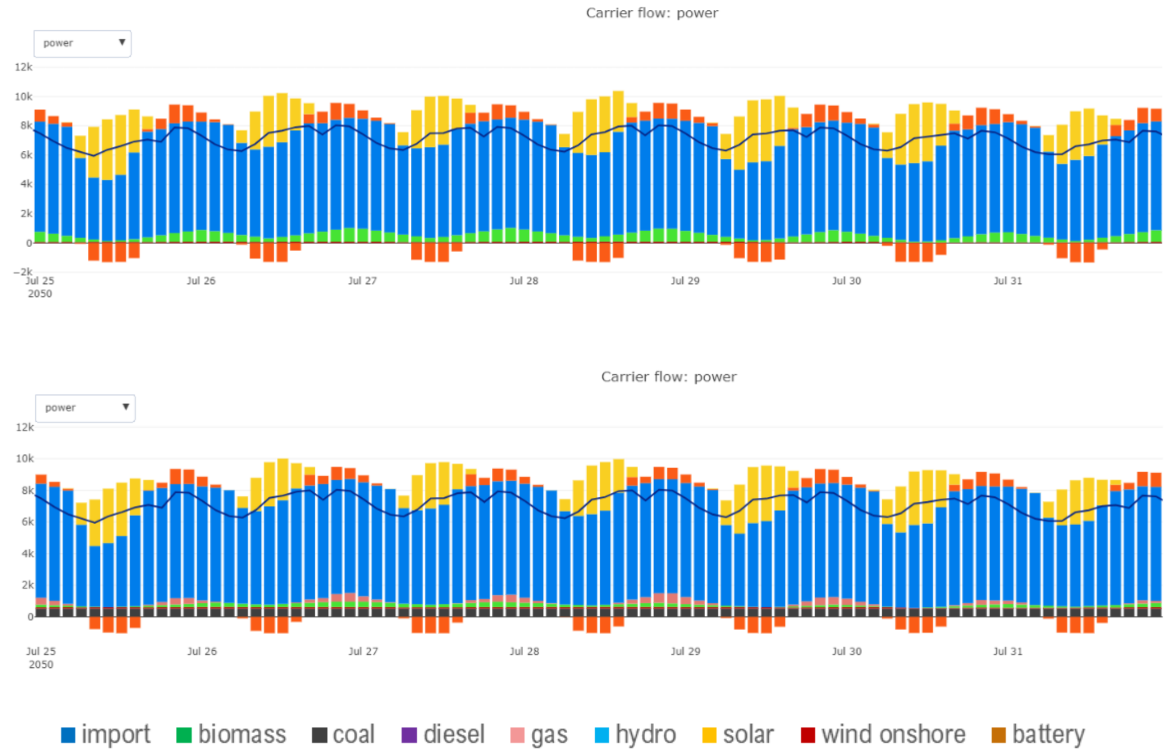

Figure 22 Comparison of the 2050 electricity generation pattern in a week. Dark blue lines represent demand. X-axis = time in 2-hour and Y-axis = MW. Sample period is Jul 25-31. Top: emission-optimization result. Bottom: cost-optimization result.

Taking a closer look into a week period, the mismatch between supply and demand in massive RE integration in 2050 is clear. **Figure 21** shows the comparison between emission-optimum and cost-optimum results from July 25-31, 2030 when the share of variable RE is low. Meanwhile, **Figure 22** shows the comparison from July 25-31, 2050 when the share of variable RE is high. In 2030 models, the balance between supply and demand can relatively be maintained because the share of variable RE is insignificant. In 2050, a mismatch between supply and demand occurs during off-peak and shoulder hours due to high solar availability but low demand. However, the excess electricity does not need curtailment as it is sufficiently stored in batteries at the same timestep and fed back to the grid when needed. Therefore, the 2050 model that relies on RE is capable to maintain the balance between supply and demand throughout the year while achieving a zero-emissions level.

4.3.4 Provincial distribution of power plants: reaching 2050 zero-emissions

4.3.4.1 West Kalimantan

In 2021, the isolated West Kalimantan grid mainly consists of diesel, coal, and imported hydro from Malaysia. By 2030, the system is planned to diversify its source of power generation with more capacity of gas, hydro, biomass, and solar. The large increase of hydro is mainly due to the big Kapuas River stretched within West Kalimantan territory. The capacity of coal is also increased to meet the growing demand. Furthermore, the West Kalimantan grid is interconnected with the other Kalimantan grid by 2030. By 2050, based on the emission-optimum scenario, hydro has the largest power capacity, while solar power capacity is slightly increased together with the deployment of batteries. Meanwhile, biomass power capacity becomes smaller and fossil fuel power capacity is phased out completely. The comparison of power plant capacity between 2021, 2030, and 2050 are presented in **Figure 23.**

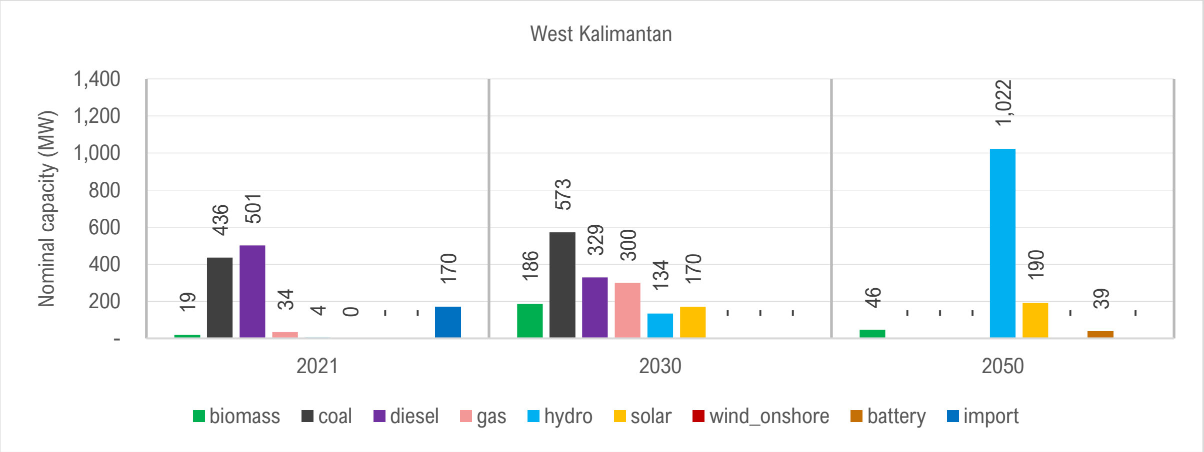

Figure 23 Comparison of the West Kalimantan power plant capacity in 2021, 2030, and 2050 based on the cost-optimum emission-optimum scenario.

4.3.4.2 Central Kalimantan

In 2021, the Central Kalimantan power system only consists of diesel, coal, gas, and a tiny amount of biomass capacity. By 2030, the role of hydro is planned to be more prominent, mainly due to the big Barito River stretched within Central Kalimantan territory. Meanwhile, the capacity of all fossil power plants is reduced, that of biomass is slightly increased, and a small amount of solar is established. By 2050, based on the emission-optimum scenario, the capacity of solar rises enormously, while that of biomass rises slightly. A reasonable capacity of batteries and onshore wind is also established. On the other hand, the capacity of hydro remains the same and that of fossil fuel is phased out completely. The comparison of power plant capacity between 2021, 2030, and 2050 is presented in **Figure 24.**

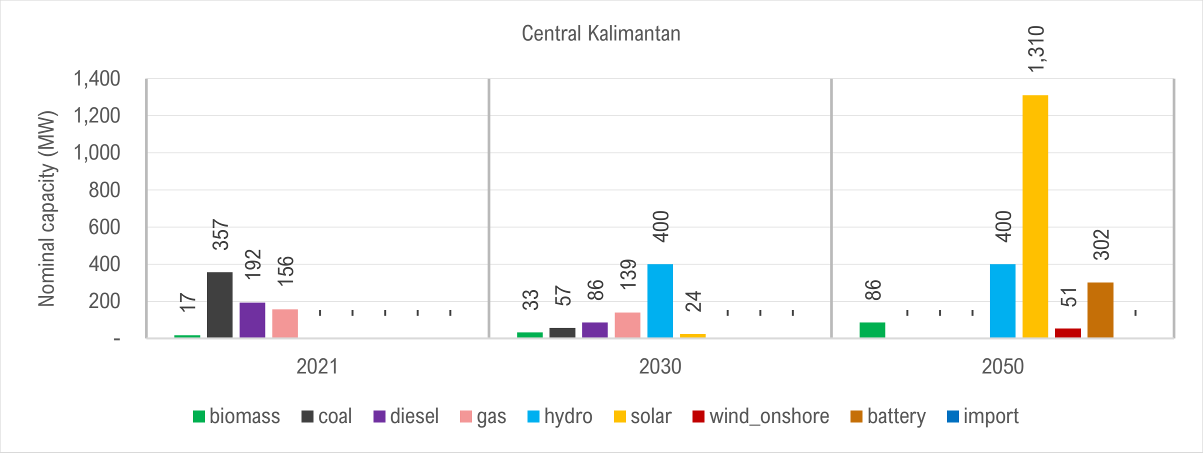

Figure 24 Comparison of the Central Kalimantan power plant capacity in 2021, 2030, and 2050 based on the cost-optimum baseline scenario.

4.3.4.3 **South Kalimantan**

In 2021, the South Kalimantan power system relies heavily on coal and consists of a significantly smaller capacity of diesel, hydro, and biomass. By 2030, despite slightly reduced, the capacity of coal is still predominant, while the capacity of gas, wind, and solar is established. On the other hand, that of hydro and biomass remains the same, while that of diesel is reduced. By 2050, based on the emission-optimum scenario, the capacity of biomass and solar rises enormously to be the main source of power capacity, while being complemented with batteries. Furthermore, that of hydro remains the same and that of fossil fuel is phased out completely. Although not described explicitly in the references, the small capacity of hydro in South Kalimantan is possibly due to its river systems mostly consisting of downstream rivers. The comparison of power plant capacity between 2021, 2030, and 2050 are presented in **Figure 25.**

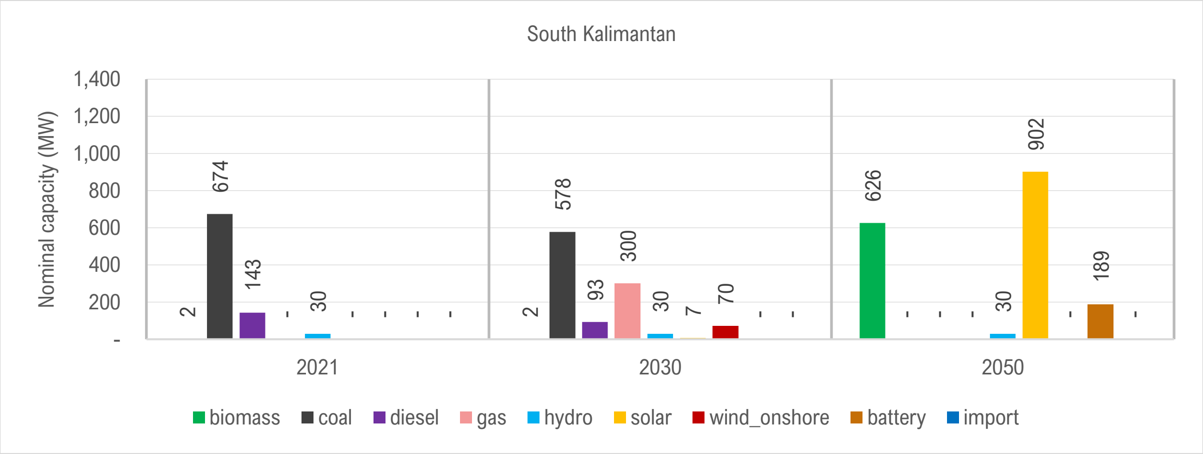

Figure 25 Comparison of the South Kalimantan power plant capacity in 2021, 2030, and 2050 based on the cost-optimum baseline scenario.

4.3.4.4 **East Kalimantan**

In 2021, the East Kalimantan power system relies heavily on coal and consists of a smaller capacity of diesel and gas and a tiny biomass capacity. It should be noticed that East Kalimantan's capacity for coal is the largest in Kalimantan, while it is also the largest coal producer in Indonesia (ESDM, 2021). By 2030, despite being reduced, the capacity of coal is still predominant, while the capacity of gas, diesel, and biomass is also reduced. On the other hand, a relatively large capacity of hydro and solar is installed. The source of hydro mainly comes from the big Mahakam River that lies within East Kalimantan territory. By 2050, based on the emission-optimum scenario, the capacity of solar rises enormously together with the deployment of battery storage capacity. The capacity of biomass also rises moderately, while that of hydro remains the same. In contrast, fossil fuels are phased out completely. The comparison of power plant capacity between 2021, 2030, and 2050 are presented in **Figure 26.**

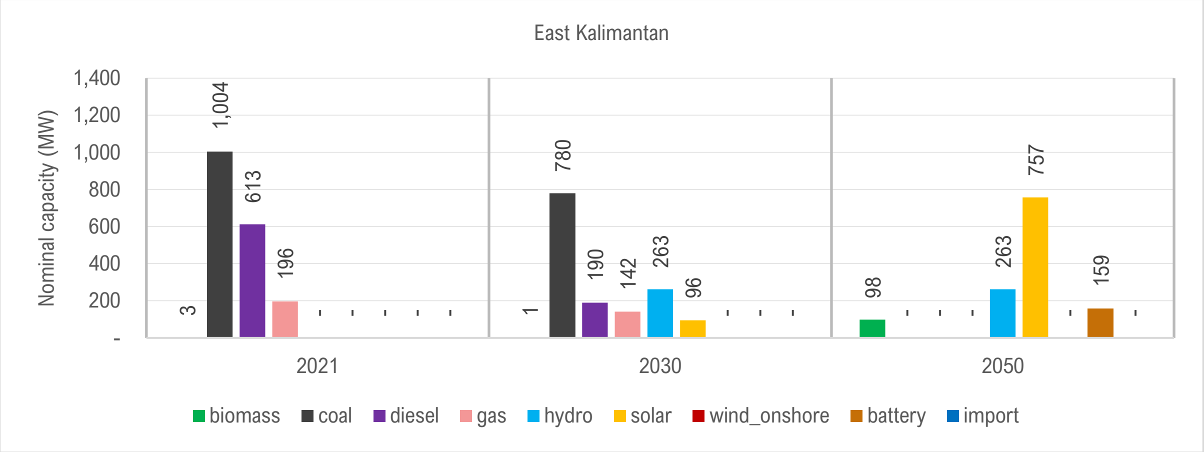

Figure 26 Comparison of the power plant capacity in 2021, 2030, and 2050 based on the cost-optimum baseline scenario.

4.3.4.5 **North Kalimantan**

In 2021, the isolated North Kalimantan power system relies on a large capacity of coal and gas together with a tiny capacity of biomass, hydro, and solar. By 2030, hydro becomes the predominant source of energy mainly due to the big Kayan river stretched within North Kalimantan territory. The capacity of gas is increased slightly, while that of diesel is significantly reduced and that of coal is completely phased out. Besides, that of solar is increased slightly. By 2050, based on the emission-optimum scenario, the capacity of hydro rises enormously to be the only type of power plant in that province. It should be noticed that North Kalimantan has the second-largest hydropower technical potential in Indonesia and the largest one in Kalimantan (ESDM, 2019). On the other hand, the other power plants are completely phased out. The comparison of power plant capacity between 2021, 2030, and 2050 are presented in **Figure 27.**

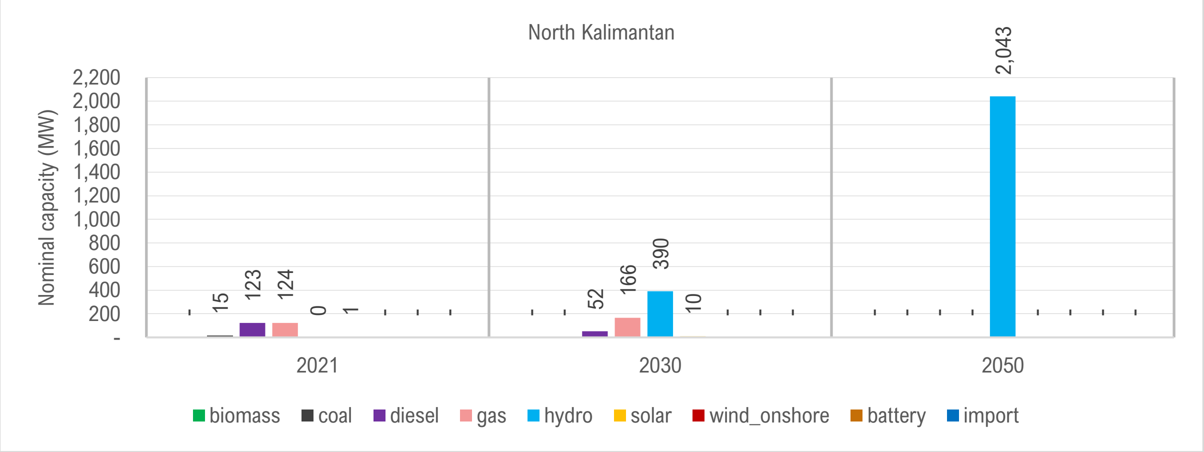

Figure 27 Comparison of the power plant capacity in 2021, 2030, and 2050 based on the cost-optimum baseline scenario.

4.3.5 System costs

The rapid integration of renewable energy from 2021 to 2050 has a large impact on the system costs as presented in **Table 9**. In all scenarios, the LCOE and RE share in the generation mix has an opposing trend. The higher the RE share in the mix, the lower the systemwide LCOE. In cost-optimum baseline scenarios, the LCOE in Kalimantan declines more than halved in the future from 72 USD/MWh in 2021 to 30 USD/MWh in 2050. A steeper decline occurs in the coal price cap annulment scenario as the LCOE decreases from 86 USD/MWh in 2021 to 30 USD/MWh in 2050. It happens as the majority of RE integration in the system comes from hydropower plants which have the lowest LCOE in Kalimantan.

Table 9 Comparison of system costs based on different scenarios

System costs	Cost optimum - baseline			Cost optimum - no coal price cap			Emission optimum	
	2021	2030	2050	2021	2030	2050	2030	2050
LCOE (USD/MWh)	72	48	30	86	58	30	59	31
Total investment (M USD)	472	587	681	472	587	713	587	759
Levelized investment (k USD/MW)	98	105	85	98	105	82	105	89

In the 2030 emission-optimum scenario, the LCOE increases significantly from 48 to 58 USD/MWh. It happens because of the significant increase of more expensive power plants such as gas and diesel in the mix to replace coal. Furthermore, in the 2050 emission-optimum scenario, the LCOE increases slightly from 30 to 31. It happens because coal and gas are mostly replaced by biomass. However, the more expensive LCOEs from biomass and batteries do not much affect the systemwide LCOE due to their small shares in the mix. The breakdown of LCOE per type of power plant and storage technology is presented in **Table 10.**

Table 10 Comparison of LCOE between different type of power plant and storage technologies

Type	LCOE (USD/MWh) cost optimum – baseline			LCOE (USD/MWh) cost optimum - no coal price cap			LCOE (USD/MWh) emission optimum	
	2021	2030	2050	2021	2030	2050	2030	2050
Battery	-	-	48	-	-	48	-	52
Biomass	76	60	55	76	55	55	55	66
Coal	60	46	43	84	73	-	61	-
Diesel	181	112,625*	-	180	419	-	134	-
Gas	82	62	73	72	55	70	55	-
Hydro	20	24	15	20	24	15	17	15
Import (hydro)	26	-	-	26	-	-	-	-
Solar	67	35	24	67	35	25	35	24
Onshore wind	-	67	46	-	67	46	67	46

**the value in 2030 is bloated due to a large diesel capacity remained but only a tiny amount of that is generated*

The trend of investment cost development can be observed from the optimization results. Based on the economic characteristics in **Chapter 4.1.3**, the investment cost of hydro, biomass, and wind is more expensive than that of fossil fuels such as coal, diesel, and gas. Solar is the only renewable that has a lower investment cost. The increase of renewables in 2030 escalates the investment cost from 98 million to 105 million USD/MW. However, in 2050, the investment cost decreases to a lower level than that in 2021 i.e. 89,205 USD/MW. It happens because of the massive integration of solar as well as the cost learning assumption that compensate the more expensive investment of hydro and biomass in the systemwide levelized investment cost.

4.3.6 CO_2eq emissions

The RE integration and phasing out of fossil fuels in the Kalimantan power system positively affect the reduction of CO_2eq emissions as presented in **Table 11**. The levelized emission of electricity generation in the baseline scenarios exceeds 0.6 ton_{CO2eq}/MWh in 2021 where more than two-thirds of the mix comes from coal. As the share of coal reduced to almost half in the mix and barely diesel generation in 2030, the emission level also decreases to around 0.5 ton_{CO2eq}/MWh. The expansion of RE capacity such as hydro, biomass, solar, and wind also contributes to the slight decline of the emission level in 2030. Furthermore, it decreases significantly to approx. 0.02 ton_{CO2eq}/MWh in 2050 where fossil fuels only account for around 12% of the mix and RE accounts for more than 80% of the mix combined.

Table 11 Comparison of systemwide CO_2eq emissions based on different scenarios

	Cost-optimum - baseline			Cost-optimum - no coal price cap			Emission-optimum	
	2021	2030	2050	2021	2030	2050	2030	2050
Emission level (kg_{CO2eq}/MWh)	682	515	67	662	458	18	368	0

The annulment of the coal price cap also positively affects the reduction of CO_2eq emissions in all modelling years. This happens because the share of coal in the generation mix decreases. However, the extent of reduced emissions depends on which power plants are used to compensate for the reduction of coal generations. In 2021, the emission level only decreases from 682 to 662 kg/MWh because gas is mostly used to compensate for the reduction of coal. In 2030, it decreases to a greater extent from 515 to 458 kg/MWh. This happens because coal generation decreases significantly. Furthermore, it decreases even further from 67 to 18 kg/MWh in 2050 because this annulment causes the coal to be passed over from the merit order of economic dispatch.

In the emission-optimum scenario, the optimum CO_2eq emission level decreases significantly in 2030 and 2050 compared to that of the other scenarios. The optimum emission level in 2030 is 368 kg/MWh. This optimum emission level in 2030 is still relatively large because RE nominal capacity only accounts for approx. 33% of the systemwide nominal capacity. If the RE capacity is maximized in the economic dispatch, it can only reduce the emission level to 368 kg/MWh. In contrast, in 2050, the RE potential capacity is larger than the total demand in the model. Moreover, the need for battery deployment does not increase the emission level since batteries also virtually produce zero emissions. Therefore, the optimum emission level in 2050 reaches zero.

4.3.7 Sensitivity analysis

The electricity demand pattern in the future is highly uncertain due to possible shifts in numerous factors such as climate, demography, economy, technology, and policy (Momani, 2013). In addition, the limitations of data available regarding the real demand profile of Kalimantan and more technically or geographically constrained hydro and biomass potentials also create more uncertainties in the result. Considering that hydro, solar, and biomass become the cornerstone of future Kalimantan power systems based on the optimization result. Sensitivity analysis is thus performed to see how the change in the demand pattern and RE potentials affect the economic dispatch optimization results, particularly related to the electricity generation mix, unmet demand, LCOE, and CO_2eq emissions.

The first sensitivity analysis is performed by modifying the standard deviation of the hourly demand curve used in the model. There are two changes i.e. doubling and halving the standard deviation of the original demand curve. The double-deviation curve represents a steeper difference between off-peak and peak demand, while the half-deviation curve represents a flatter difference between them. It should be noticed that the total demand in a year remains the same. The only difference is in the standard deviation that affects the extent of polarity between peak and off-peak. The comparison between the demand curves used in the sensitivity analysis is presented in **Figure 28**.

The second sensitivity analysis is performed by reducing the availability of hydro and biomass resources. There is only one change i.e. halving the maximum potential capacity of both. It means the model still has the same maximum capacity potential as the other technologies. This analysis comes from the fact that drought leads to a lower crops harvest which in consequence may cause problems on the supply side of both hydro and biomass power plants simultaneously (Jurasz et al., 2020).

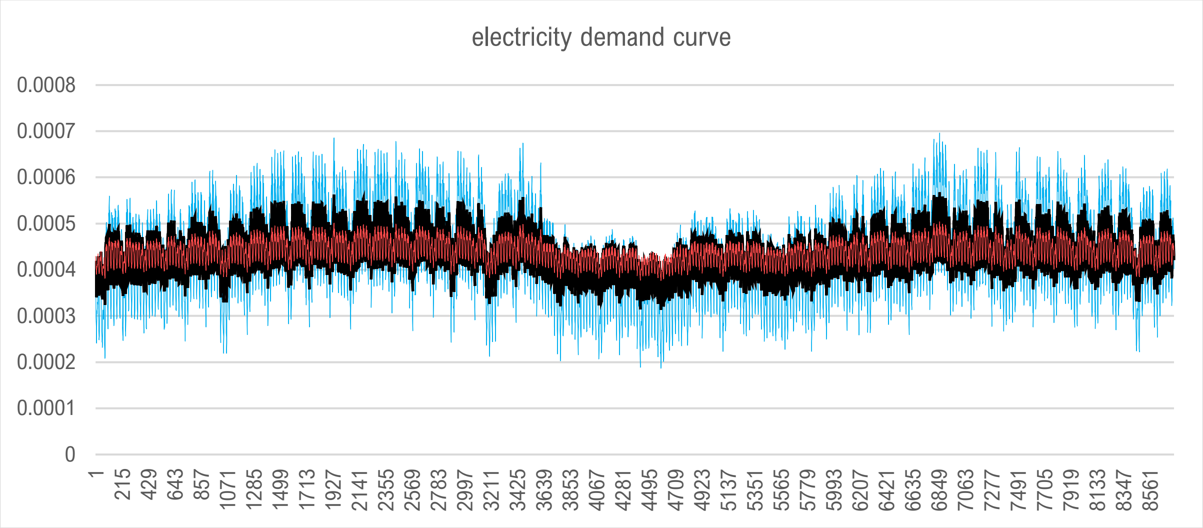

Figure 28 Comparison of three different demand curves for sensitivity analysis. All curves represent identical total demand but different standard deviation. Black: original demand curve. Blue: double-deviation demand curve. Red: half-deviation demand curve.

4.3.7.1 Sensitivity of demand curve pattern

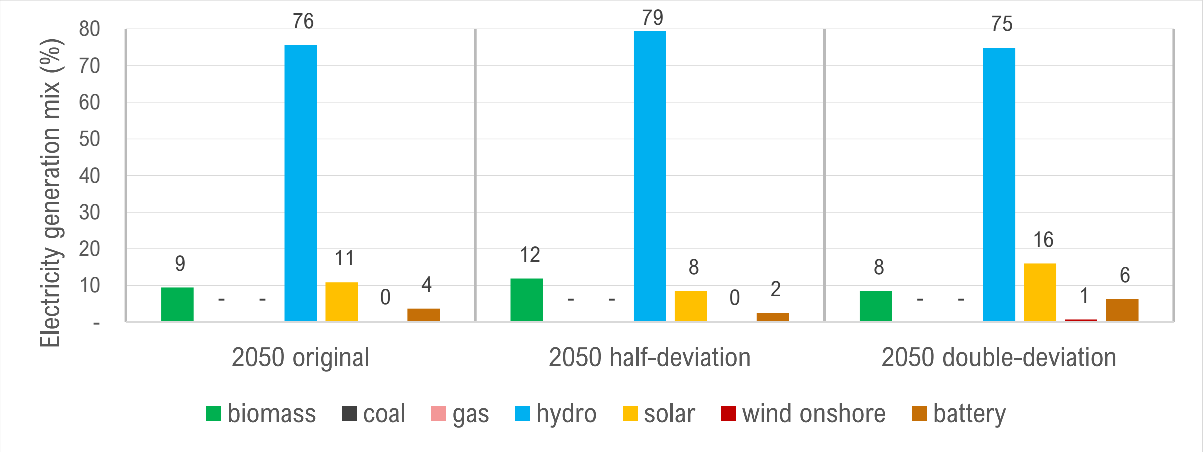

Figure 29 Comparison of electricity generation mix from cost-optimization results for sensitivity analysis in 2050.

The comparison of the electricity generation mix between different sensitivity analyses is presented in **Figure 29.** The electricity generation for three different demand curves shows a shift of hydro, solar, and biomass in the emission optimum 2050 scenario as shown in **Figure 30**. If the demand curve deviation is small, hydro and biomass generations are maximized, while solar and onshore wind generations are reduced. It then reduces the share of batteries in the mix because the demand during shoulder hours becomes larger and that of peak hours becomes smaller, resulting in a better match between the demand and variable RE generation. In contrast, if the demand curve deviation is large, hydro generation in the mix declines moderately. This happens because a larger amount of its capacity is only utilized during peak hours. Smaller baseload also reduces biomass generation in the mix. Meanwhile, a combination of solar generation and batteries increases moderately to compensate for this situation.

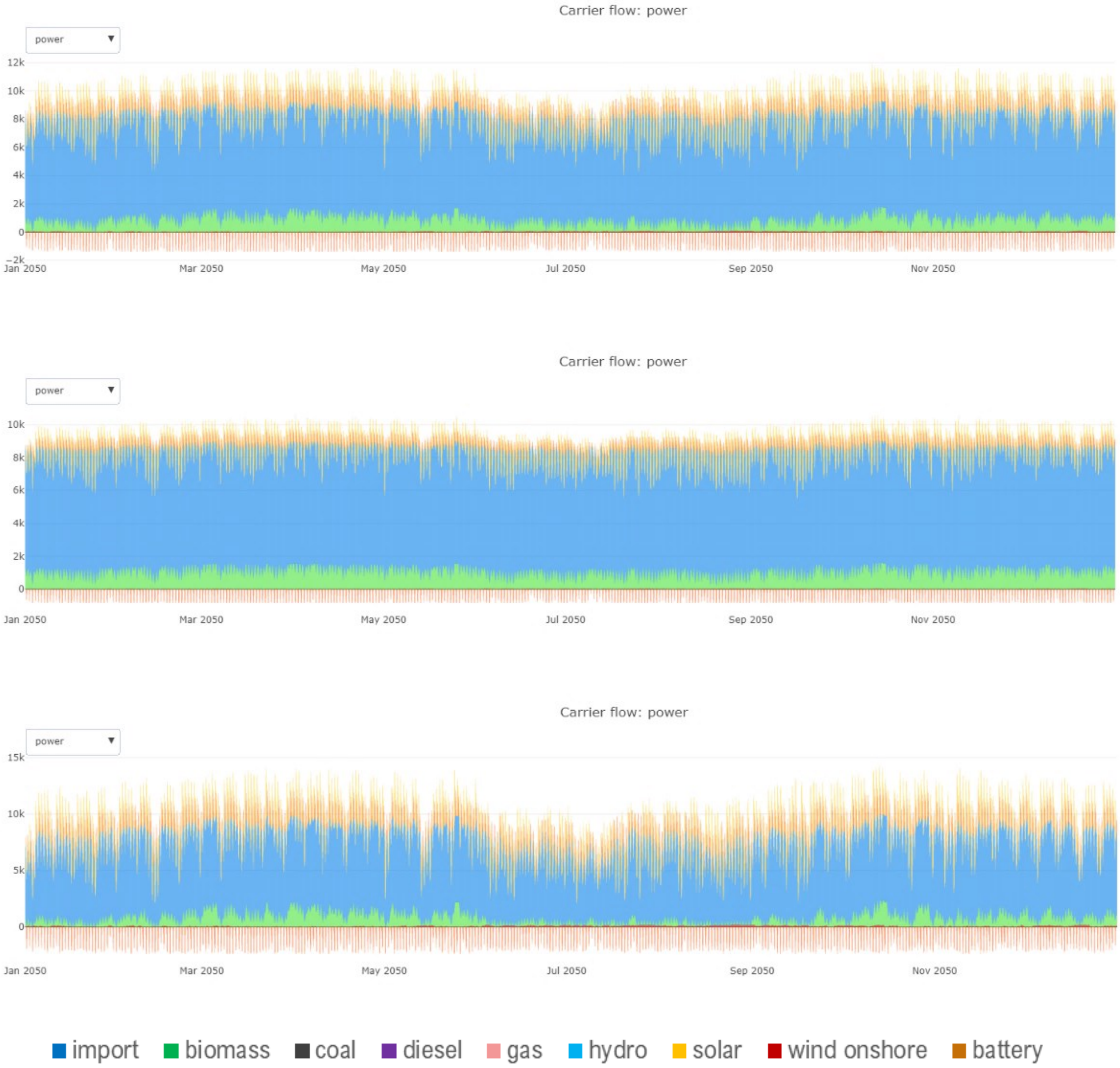

Figure 30 Comparison of economic dispatch using the 2050 emission optimum scenario for sensitivity analysis. X-axis = time in 2-hour and Y-axis = MW. Top: original. Middle: half-deviation. Bottom: double-deviation.

In terms of LCOE and CO_2eq emissions, the changes in the demand curve also affect the system differently. If the demand curve deviation is halved, the LCOE declines from 31.29 to 30.12 USD/MWh. This decline happens because more power capacities can be utilized. It means demand-side management that lessens peak demand can help lower the LCOE. In contrast, if the demand curve deviation is doubled, the LCOE rises to 34.24 USD/MWh. This happens because the utilization of hydro, biomass, and solar declines in order to reserve capacity to meet the steep peak demand. This results in power plants having a higher LCOE than those in the flatter demand curve. Therefore, a large deviation between peak and off-peak demand requires sufficient capacity of cheap peaking power plants to fulfil the demand without increasing the system costs significantly. Besides, the sensitivity analysis does not impact the already zero-emissions level because the maximum potential capacity of RE combined is still sufficient to meet all the demand at every timestep.

4.3.7.2 Sensitivity to availability of hydro and biomass resources

Figure 31 Comparison of economic dispatch cost-optimization with zero emissions result for sensitivity analysis in 2050. X-axis = time in 2-hour and Y-axis = MW. Top: original. Bottom: half potential of biomass and hydro.

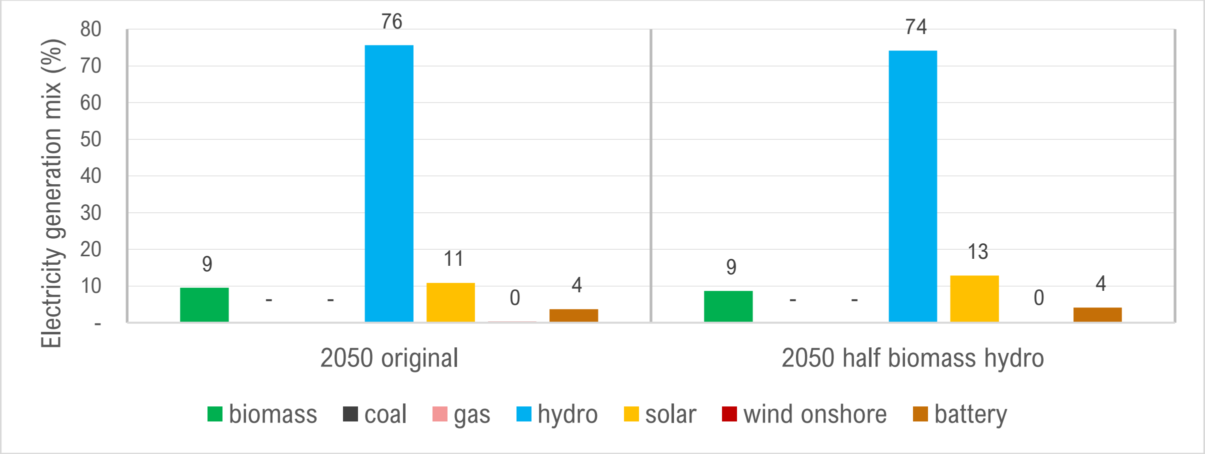

Figure 32 Comparison of electricity generation mix for the sensitivity to biomass and hydro variability in 2050.

The electricity generation for the half potential of biomass and hydro shows a shift in the 2050 economic dispatch and electricity generation mix as shown in **Figure 31** and **Figure 32,** respectively**.** Halving the maximum potential of biomass and hydro implies the slight reduction of biomass and hydro generations in the mix. The role of solar and batteries also increases to compensate for the reduction of biomass and hydro, while the role of onshore wind is slightly reduced. Halving the maximum potential of biomass and hydro also affect the LCOE. The LCOE increases slightly from 31.29 to 32.44 USD/MWh. It happens because of the lower share of cheap hydro. Therefore, a possible variability of biomass and hydro resources requires sufficient capacity of other inexpensive, clean power plants with stable resource supply to maintain a low system cost. Besides, the sensitivity analysis does not impact the already zero-emissions level because the maximum potential capacity of RE combined is still sufficient to meet all the demand at every timestep.

Chapter 5

Interrelation between Energy Justice and Energy Transition in the Kalimantan Power System

5.1 Energy justice interviews

The energy justice analysis is based on the comparison between the interview with various stakeholders related to the actual situation in the Kalimantan power system and the data obtained from the optimization. Meanwhile, the optimization results are evaluated in terms of energy justice parameters i.e. affordability, availability, intragenerational equity, and intergenerational equity. The summary of the interview result per stakeholder is presented in **Table 12**.

Table 12 Summary of the interview result per stakeholder

ID	Occupation	Energy justice parameters			
		Affordability	Availability	Intragenerational equity	Intergenerational equity
01	Resident	- No complaints about the electricity tariff	- Blackout happens approx. once/month for maintenance - Unprecedented blackout happens during floods	- The cost burden of grid expansion to an unplanned region is charged to the requester - Coal mining activities causes deforestation that causes more frequent floods - Only rich residents and large buildings have private diesel gensets	
02	Resident	- No complaints about the electricity tariff	- Blackout happens approx. 2-3 times/year for maintenance - Unprecedented blackout happens during thunderstorm or floods	- Only rich residents and large buildings have private diesel gensets	
03	Resident	- No complaints about the electricity tariff	- Blackout happens approx. once/month for maintenance - Rolling blackout still happens frequently in rural areas - Unprecedented blackout happens during thunderstorm or floods	- Urban residents can easily request a PLN grid service via a mobile app	
04	Govt official / resident	- Overdue electricity bills still happen regularly every month - Most overdue electricity bills happen to subsidized customers - PLN electricity tariffs are identical in the entire Indonesia based on each consumer category		- Many rural regions are unreachable to PLN grid expansion - Unplanned PLN grid expansion can be requested, but needs to conduct feasibility study	
05	Govt official		- Coal power plants are available with high CF for baseload, but not available for peaking power		- Hydropower is planned to be the main source of future Kalimantan power system

ID	Occupation	Energy justice parameters			
		Affordability	Availability	Intragenerational equity	Intergenerational equity
06	Govt official / resident	- No complaints about the electricity tariff	- Blackout happens several times/year for maintenance - Rolling blackout still happens frequently in rural areas - PLN will provide a prior notice about rolling blackout to govt offices in these areas, but not to regular residents		
07	NGO / resident		- Security of supply for biomass/biogas power from oil palm due to its abundant plantations and constant, continuous harvest	- Govt electrification ratio includes private diesel gensets - Some off-grid communities get electricity access from big mining or plantation companies - Hundreds of villages do not have an access to PLN grid service	
08	NGO		- Security of supply for the rural biogas power projects is sufficient for the entire year		
09	Coal mining / resident	- No electricity bill	- Self-generated diesel power plant, thus blackout never happens	- Nearby rural communities do not have an access to PLN grid service, thus getting electricity supply from the company's excess power - Visible air pollutions do not enter surrounding areas due to a strict environmental regulation	- The company's top management has given a direction to diversify its business portfolio to renewables such as solar PV market - Coal power plants (incl. coal mines) may still operate in the future (2050)
10	Coal power plant		- Coal power plants are available with high CF for baseload, but not available for peaking power - Diesel and gas power plants are available to fulfil both baseload and peak demand	- Visible air pollutions do not enter surrounding areas due to a strict environmental regulation - Coal supply in Java comes from Kalimantan	- Coal power plants (incl. coal mines) may still operate in the future (2050) - Western spare part suppliers are reluctant to supply coal plants anymore to support coal plant phase out

5.2 Energy justice analysis

5.2.1 Affordability

5.2.1.1 **Costs of RE integration**

The electricity tariffs are the amount of money the consumers need to pay to secure electricity supply from the grid. The electricity market in Indonesia preserves an artificial monopoly, meaning that the tariffs are regulated by the government. These tariffs are uniform in every region in Indonesia (ESDM, 2016). There are at least thirty-seven categories for the regulated electricity tariffs, but they are aggregated into three main categories in this research for simplification i.e. subsidized, industrial (med- and high-voltage), and household (low-voltage).

For regular customers, med- and high-voltage industrial customers (200–30,000 kVA) get a lower tariff in 2021 i.e. 71 USD/MWh, while low-voltage household and business customers (1.3–200 kVA) get a higher tariff i.e. 93 USD/MWh. The household tariff is around 30% more expensive than the industrial tariff because PLN needs to invest in transformers and low-voltage distribution grids for this kind of customer (Dhany, 2016). Lastly, subsidized household customers (≤0.45 kVA) get an exceptionally low tariff i.e. 29 USD/MWh. This tariff only applies to households with installed power capacity smaller than, inclusive, 450 VA (ESDM, 2016). Meanwhile, the cost-optimum LCOE in the 2021 model is still higher than the industrial tariff. Considering that the electricity tariff also includes a profit margin and other operating costs, the LCOE of the real-life Kalimantan power system might be higher than the LCOE obtained from the model. It can be seen at the average BPP in 2021 that reached 94 USD/MWh (ESDM, 2021b), higher than the regular household tariff in the same year. Therefore, this comparison is intended to provide insights regarding the impact of RE integration on the LCOE development between modelling years which may eventually influence the tariff decision-making in the future. The comparison between the actual tariffs and the LCOE from optimization results is presented in **Table 13**.

Table 13 Comparison of system costs based on different scenarios

System costs (USD/MWh)	Actual tariff 2021			Actual 2021	Cost optimum - baseline			Cost optimum - no coal price cap			Emission optimum	
	Subsidized	Industrial	Household	BPP	2021	2030	2050	2021	2030	2050	2030	2050
LCOE					72	48	30	86	58	30	59	31
Value [*]	29	71	93	94								

** assuming 1 USD = 14,500 IDR*

The cost-optimum LCOE keeps declining from 2021, 2030, to 2050 as presented in **Table 11**. At the same time, the share of RE in the electricity generation mix keeps rising. It happens due to several reasons. Hydro is always the cheapest option in Kalimantan for every scenario in terms of LCOE. Moreover, solar is also an inexpensive option compared to fossil fuels. Meanwhile, biomass, onshore wind, and batteries are relatively more expensive. Choosing which types of RE technology to integrate into the system is thus crucial in providing affordable electricity tariff in the future.

Based on the optimization results, the massive integration of hydro with diversification with biomass, solar, onshore wind, and batteries in the future Kalimantan power system can be a solution to tackle energy injustice by helping provide more affordable electricity tariffs. The attempt at this integration is supported by the large potential of these RE technologies available in Kalimantan. In addition, phasing out coal and gas gradually in the future does not negatively affect the systemwide LCOE if it is mostly replaced by these cheap RE technologies. Moreover, the coal price cap policy in 2050 only affects the LCOE moderately because the share of coal in the mix is becoming peripheral. Furthermore, the cost-optimum and emission-optimum LCOEs in 2050 are becoming almost as cheap as the subsidized tariff in 2021. It means the subsidized tariff can be made cheaper in the future. Or the burden of subsidy on the government side can be lower if the level of subsidized tariff remains similar. However, it should be noticed that these results are highly influenced by future cost assumptions and future inflation is not considered.

5.2.1.2 **Affordable electricity tariffs – for everyone?**

There are three aggregated categories of regulated electricity tariffs in entire Indonesia i.e. subsidized, industrial, and household. The subsidized tariff is intended to help the lowest-income group afford electricity supply at homes. It is more than three times cheaper than the regular tariff for households i.e. 29 and 93 USD/MWh respectively. Moreover, only households under the poverty line can apply for the installation of subsidized electricity services (Dhany, 2015). The average electricity bill for the subsidized customers is 3.41 USD/month, which equals approx. 0.12 MWh/month (Beritagar, 2017). For comparison, Indonesia's electricity consumption per capita in 2020 is 1.09 MWh (BPS, 2022). Considering the maximum income of Indonesian households below the poverty line in 2020 is 41.38 USD/month (Government of Bantul, 2020), the average subsidized electricity bill accounts for approx. 8.2% of their income.

The average electricity consumption for Indonesian grid-connected households (all categories incl.) in 2021 is around 0.13 MWh/month (PLN, 2022). Using the regular tariff, it can be derived that the average electricity bill for these consumers is around 12.12 USD/month. On the other hand, according to a news report, the average electricity consumption for regular households (1,300 VA) is assumed to be 0.48 MWh/month, which equals 44.75 USD/month (Dewi, 2020). This assumption is also validated by the interviews with ID01 and ID02, mentioning that their electricity bills are around that level partly due to having multiple air conditioners (AC) and televisions in a single house. According to UNESCAP (2019), the AC ownership rate of Indonesian households is estimated to be 24% in 2018. This rate does not take into account the number of AC at home, which may vary between different households.

In addition, the average regional minimum salary in Kalimantan in 2021 is approx. 207.96 USD/month (BPS, 2021). That amount of average regular electricity bill means that to afford the average convenience level in terms of electricity consumption, assuming both husband and wife in a household have a job, the electricity bill can burden around 11% of the low-income groups above the poverty line who cannot apply for the subsidized electricity service.

The same electricity tariff applies to much richer households with a salary multiple times higher than the low-income groups. Based on the interviews of four residents from different regions in Kalimantan (i.e. ID01, ID02, ID03, and ID06), the interviewees perceive the current electricity tariffs as affordable. And they have no complaints whatsoever regarding how PLN regulates the tariffs. An important thing they consider related to electricity consumption is how they need to avoid overusing electrical devices in homes such as air conditioners or televisions so that their bills do not skyrocket. However, they are regular customers coming from middle- and high-income groups. It means the burden of their electricity bills is much smaller than their household income.

The subsidized customers experience a contrasting situation. The interview with ID04 reveals that most permanent power disconnection cases due to payment overdue happen on the subsidized customers (450 VA). He also mentioned:

"Despite their electricity bill being only 1-2 USD/month, some subsidized customers still cannot afford to pay regularly. Sometimes we even need to uninstall the grid connection from their houses completely because they fail to pay that extremely cheap bill for three consecutive months."

Currently, the coal price cap helps provide a cheaper LCOE based on the optimization results. However, as the share of coal in the generation mix is expected to diminish gradually to achieve the net-zero emission target, the price cap should not be relevant anymore in the future. Therefore, looking at the declining trend of the systemwide LCOE in the future, the system expansion and integration of RE in the Kalimantan power system has the potential to help tackle this unjust affordability by providing a cheaper electricity tariff to the low-income groups above and below the poverty line without further burdening the government budget for coal subsidy.

Nevertheless, the declining trend of LCOE does not capture the future worth of this value. The LCOE calculation in the optimization model uses the US dollar (USD) as the currency, while Indonesia uses the rupiah (IDR). Based on the data, 1 USD in 1991 is equivalent in purchasing power to approx. 1.99 USD in 2021, while 1 IDR in 1991 is equivalent to approx. 11.30 IDR in 2021 due to its volatile inflation rate (Official Data Foundation, n.d.). How much the 2050 LCOE is equivalent to today's money in Kalimantan might indicate that it is not as cheap as it seems. It means that the declining trend of LCOE in the future may not necessarily improve the purchasing power of the most vulnerable and low-income groups in terms of affordable electricity tariffs.

To address this issue, reshaping the electricity pricing scheme in the future can be a solution. As mentioned in the earlier paragraph, the PLN tariff for regular household consumers is the same regardless of their income in entire Indonesia. Meanwhile, a person's purchasing power is based on household income (CBS, 2007). It also means that the electricity demand of the lower-income households may not be as high as the higher-income households in the same PLN tariff category. An ascending block rate tariff can be implemented to address this injustice issue (Sovacool & Dworkin, 2015). A block rate tariff charges customers a different price depending on how much electricity they have used (Wrigley, 2017). Therefore, those who use more will pay a higher tariff, while those who use less will pay a lower tariff, providing wider justice among different groups of consumers.

5.2.2 Availability

5.2.2.1 **Reliability of RE-dependant power system**

There are two distinct categories of RE technologies in the Kalimantan power system. The first one consists of dispatchable power generators such as biomass and hydro that are capable to provide baseload power due to their relatively stable resources. Reservoir hydropower can be further dispatched as load-following and peaking power plants if the amount of water in the reservoir is sufficient. In reality, biogas can also be dispatched as peaking power plants, but it is aggregated into biomass in this research. The second one consists of variable power generators such as solar PV and wind. It means they are not capable to cover baseload demand at all times (IRENA, 2015). Fulfilling baseload is important because a certain minimum of electricity must be maintained in the grid to ensure the prevention of blackouts or system failures (Matek & Gawell, 2015), which is related to energy justice in terms of electricity service availability.

If not being managed properly, the power system can face a serious issue in balancing the variable renewable energy supply and demand. However, based on the 2050 emission-optimization scenario, solar PV generates electricity approx. 12 hours per day for the entire year in all regions of Kalimantan. This result gives some sort of predictability, but low capacity factors and daily variability can still be a drawback. In Kalimantan, solar PV panels begin to generate a tiny proportion of their nominal capacity at around 6 a.m. when the sun rises. It reaches its daily peak of generation between 11 a.m. to 1 p.m., depending on the weather at that time, while the demand is relatively low. Then, its generation starts declining until the sun sets at approx. 6 p.m.

The absence of solar energy coincides with the peak demand at around 7-9 p.m. Overall, the capacity factor of solar is only around 15-16% in all scenarios. However, the pattern of solar generation is quite predictable to manage the system reliability. Although, the amount of electricity generated each day during the same period is erratic. Sometimes, its peak generation is higher than that of the previous day, but at the same time the demand is lower than that of the previous day. The generation pattern of solar, wind, and batteries in the 2050 emission-optimum scenario is presented in **Figure 33.**

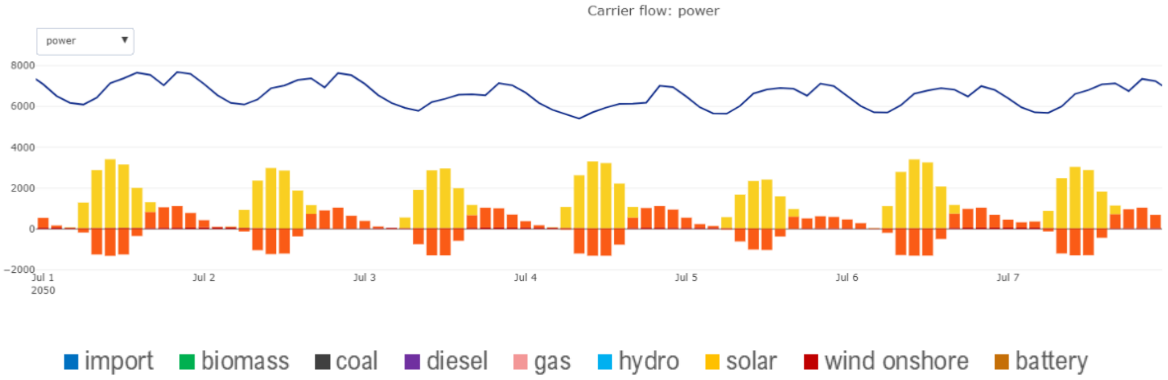

Figure 33 Different patterns between demand (blue lines), onshore wind generation (dark red, not clearly visible in this graph due to its marginal share in the mix), solar generation (yellow), and battery storage charge/discharge (orange) during a week-period of Jul 1-7 based on the 2050 emission-optimum scenario. X-axis = time in 2-hour and Y-axis = MW.

Theoretically, a large share of wind power generation can be a solution to complement the absence of solar energy during nighttime as it complements each other. However, the variability of wind generation in Kalimantan is even more irregular than that of solar generation as presented in **Figure 34**. While the pattern of solar generation is relatively constant throughout the year, that of wind-solar generation varies significantly. Wind energy in Kalimantan is available for most periods from June-October and December, while it is relatively “windless” with a massive deviation for many other periods in a year. Overall, the capacity factor of onshore wind is only 22% and 27% in 2030 and 2050 respectively. This difference occurs because the locations of onshore wind differ between 2030 and 2050. This result also does not yet take into account the variability of weather between different years in real life.

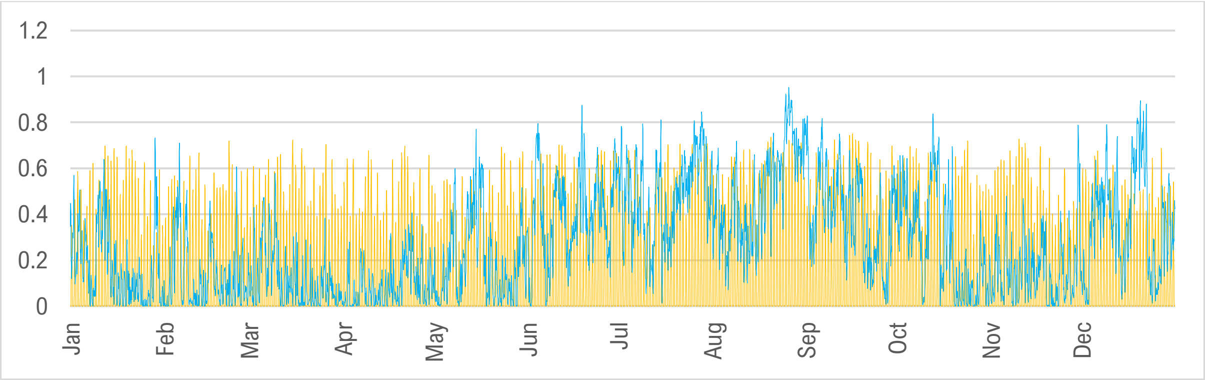

Figure 34 Comparison of the variability of availability between solar (orange) and onshore wind (blue) in their respective electricity generation per capacity (MWh/MW) per year.

A sudden, unpredicted drop in solar and wind power generation due to unfavoured weather conditions during peak hours can result in insufficient supply. This may lead to rolling blackouts that, in most present-day cases, the TSO decides to cut off the load from consumers in rural areas. To maintain system reliability in this case, a sufficient capacity of peaking power plants such as hydro and gas power plants is crucial to balance the supply and demand when this kind of unprecedented problem occurs (Busby et al., 2021). Another solution is also adding energy storage technologies to the grid such as lithium-ion batteries. The stored electricity from solar and wind in batteries can be fed back to the grid to help fulfil the high demand during a period of a combination of low wind and no solar availability, for instance on April 8th between 6 and 11 p.m. as shown in **Figure 35**. This demonstrates the capability of the RE-dependent power system to maintain system reliability.

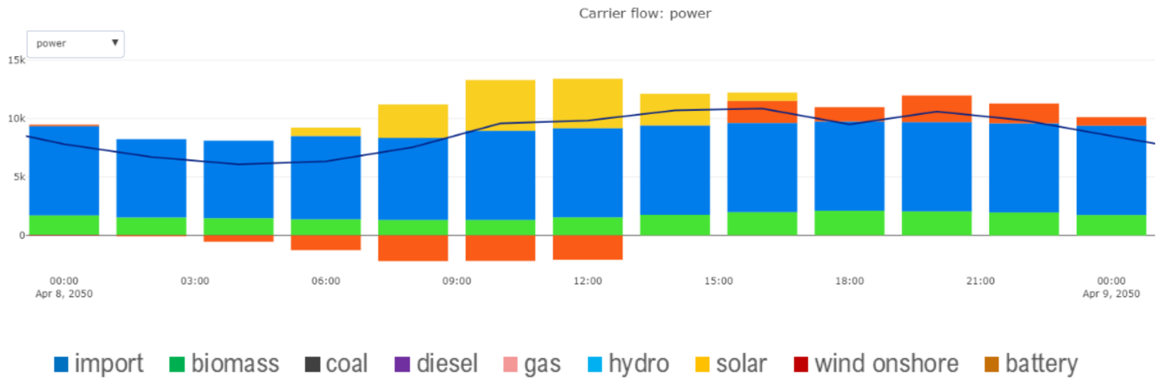

Figure 35 Comparison between electricity supply and demand in April 8th, 2050 based on double-deviation demand sensitivity analysis. Solar (yellow) and wind (dark red) generations are almost completely not available simultaneously during peak hours between 6-11 p.m. Electricity supply from batteries (orange) becomes necessary to help meet the high demand in the absence of solar and wind. X-axis = time in 2-hour and Y-axis = MW.

5.2.2.2 Development of availability in the Kalimantan power system

Based on the interviews, the availability of electricity supply in Kalimantan in the past (more than five years ago) was poor. Rolling blackouts due to insufficient supply occurred 2-3 times a week with a duration ranging from 2 to 8 hours in a day. No prior announcement was provided by PLN to households regarding at what time a rolling blackout would happen. However, government offices would receive a prior announcement regarding this matter. Most high-income households, businesses, and industries had diesel generators to provide their own electricity during blackouts.

In present days, based on the interviews, the rolling blackouts barely happen anymore. Blackouts still occur sometimes, especially due to maintenance or repair. In the West Kalimantan case, the electricity import from Malaysia helps improve the system's reliability. Overall, the ample capacity of coal, gas, and diesel power plants is one of the main reasons for the reliability improvement of the Kalimantan power system in 2021. Nevertheless, the unjust availability of electricity services still exists in the present day. The declining case of blackouts only occurs in urban and suburban areas. Many grid-connected households in rural areas in Kalimantan still experience rolling blackouts frequently.

As more RE capacities are integrated into the future Kalimantan system, its availability in all regions is improved. For instance, in the 2050 cost-optimization result, abundant potentials of both dispatchable and variable RE can balance the system without having any unmet demand for the entire year. Phasing out diesel and declining the roles of coal and gas in the future power system does not necessarily impair the system's reliability. Large capacities of hydro, solar, and biomass, including smaller capacities of wind and batteries, can compensate for the reduction of coal and gas in the system. However, this result does not take into account the unprecedented weather conditions that may encourage drought, crop failures, less solar irradiation, or lack of wind availability in the future.

The 2050 optimization result also shows the improvement of the security of supply as the system is capable to provide sufficient supply in West Kalimantan without having to import electricity from Malaysia. Moreover, without a single fossil fuel power plant, the future Kalimantan power system is capable to handle the mismatch between variable RE generations and the demand by the deployment of utility-scale battery storage combined with hydropower reservoirs as peaking power plants. This is possible due to the large potential of these RE resources in Kalimantan, despite the constraints formalized in the models as described in **Chapter 4.1.4**. Thus, the future Kalimantan power system is capable to provide 24/7 electricity supply to consumers in all Kalimantan regions, improving the availability of the present Kalimantan power system.

5.2.3 Intragenerational Equity

5.2.3.1 An unequal access to the present power system

The present Kalimantan power grid is not entirely connected. Furthermore, many rural regions do not have an access to the grid as the present electrification ratio in Kalimantan does not yet reach 100%. In 2021, Central Kalimantan has the lowest electrification ratio i.e. 88.27%, followed by West Kalimantan, North & East Kalimantan, and South Kalimantan i.e. 93.24%, 94.81%, and 99.67% respectively (PLN, 2022). However, the electrification ratio does not take into account the quality and reliability of electricity access as it includes those getting electricity access for less than two hours per day (Setyowati, 2020).

The electrification ratio of is assumed to be 100% in all future scenarios based on the product of demand per person and total estimated population in 2030 and 2050. Although, this assumptions only takes into consideration that all residents are connected to the PLN grid in the future, while this may not be the case in real life. Both the overcapacity of coal power plants mentioned in **Chapter 4.3.2** and the optimization result with a 100% electrification ratio indicate that the current power generation capacity in Kalimantan is capable to meet all the demand in Kalimantan. However, the Kalimantan power system expansion depicted in the models can demonstrate that a low electrification ratio in 2021 occurs not because of insufficient power capacity but because some regions in Kalimantan are not yet connected to the main high-voltage transmission network. Furthermore, some existing high-voltage transmission networks are also not connected to each other as shown in **Figure 36**. This means that the abundant capacity of power plants in some regions of Kalimantan cannot supply the demand in some other regions because their grids are not connected.

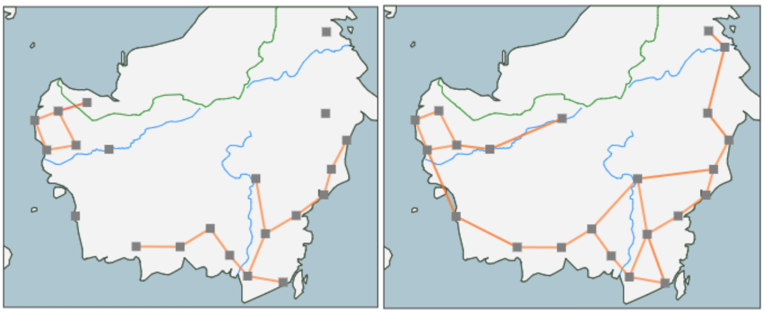

Figure 36 Expansion of the simplified Kalimantan power system as formalized in the models. Left: 2021. Right: 2030 and 2050.

Several intragenerational inequities are also revealed in the interviews. According to ID05, ID06, ID07, and ID09, many communities in rural Kalimantan cannot access the grid-connected electricity service provided by PLN. Apart from that, the housing complexes owned by mining and oil companies in rural areas have electricity access 24/7 because they generate their own electricity using diesel power plants. Meanwhile, there are some nearby rural communities without electricity service access from PLN. Thus, these companies sell their excess power to nearby communities, which the optimization model developed in this research is not able to capture. This unequal access to the electricity service does not happen to rural households only. ID01 mentioned:

"*A few years ago a family member of mine worked at a newly-built factory in South Kalimantan. It was located at an area where a grid connection did not exist yet. The factory then requested a grid connection to PLN. After the connection was built, the factory was charged with a more expensive electricity tariff than what had been regulated due to a kind of levy for the network expansion."*

In general, ID05 mentioned that PLN will conduct an economic feasibility study before deciding to build an access to new customers located away from the existing grid. This feasibility study is intended to determine whether the network expansion to an unplanned area is economically viable to PLN or not. One of the reasons is that the lower population densities in rural areas, and thus lower electricity demand, do not justify the huge investments associated with the development of the grid infrastructure (Veldhuis & Reinders, 2015). However, the finding mentioned by ID01 also indicates that the cost of unplanned grid expansion becomes a burden of the requester.

5.2.3.2 **Distributed benefit and burden**

The fossil fuel-dependent Kalimantan power system is beneficial in providing fair electricity service access to everyone in the present day. Based on the 2021 cost-optimization result, coal is the second cheapest source of energy in Kalimantan in terms of LCOE after hydro i.e. 59.66 USD/MWh respectively. However, the capital cost of a coal power plant is lower than that of hydro i.e. 1.65 and 1.90 million USD/MW respectively. Thus, a coal-based power system in Kalimantan is relatively inexpensive to develop and operate. Nonetheless, it should be noticed that the coal price cap policy contributes to the low LCOE of coal power plants in 2021.

The massive share of fossil fuels in the 2021 cost-optimum electricity generation mix (94.87%) is one of the attempts by the government to distribute the benefits of electricity access in Kalimantan fairly. However, if the price cap is annulled, the systemwide LCOE rises from 71.02 to 86.30 USD/MWh in 2021. This happens because the actual coal market price in 2021 reached its highest level in the last decade (ESDM, 2022), which would strongly affect the burden of subsidies for the low-income groups. This system also produces 682.34 kg/MWh of CO_2eq emissions in 2021. At the same time, based on the interviews, upstream deforestation due to coal mining activities causes more frequent flooding in some regions in South Kalimantan. More frequent flooding leads to more frequent blackouts due to power grid disruptions. It does not yet take into account the environmental effect caused by the coal mines. Although, the environmental regulation has strictly prevented visible air pollution spread out of the sites. Thus, the burden of the fossil fuel-dependent system needs to be considered.

In a meantime, the large potentials of hydro, biomass, and solar energy in Kalimantan can be beneficial in distributing benefits such as better electricity access with much lower emissions or lower costs since they virtually generate zero emissions and have a lower LCOE than gas and diesel. For instance, the source of biomass power is abundant in rural oil palm plantations where the unequal electricity service access exists. And some solar PV potential sites are located in areas that have a significant distance from the existing PLN grid according to the map in Pragt (2021).

While the consumers have the right to get fair access to clean electricity, the lack of system interconnection in 2021 hinders the distributed benefit of the power system. For instance, the benefit of imported hydropower in the north-western part of West Kalimantan cannot be distributed to the other West Kalimantan regions such as Kapuas Hulu or Ketapang because their transmission network is not interconnected. This situation has forced these regions to still rely heavily on diesel power. Meanwhile, according to a news report, a PLN high-ranking official claimed that the electricity import cost is cheaper that the generation cost from diesel power because the imported electricity is generated from a large hydropower plant (Wicaksono, 2017), which the optimization result also indicates the same as the LCOE of hydropower is cheaper than that of diesel power.

5.2.4 Intergenerational Equity

5.2.4.1 **Energy transition – for better or worse?**

Based on the optimization results, the 2050 Kalimantan power system has the potential to provide more affordable, cleaner, and reliable electricity compared to the 2021 counterpart. With 96.30% of RE share in the electricity generation mix, compared to only 1.79% of that in 2021, the LCOE in the emission-optimum 2050 becomes more than twice less expensive i.e. 31 USD/MWh compared to 72 USD/MWh in 2021. The future emission level is also reduced from 682 kg_{CO2}eq/MW in 2021 to zero in 2050. In addition, the high shares of dispatchable RE in the mix such as hydro (74.95%) and biomass (9.49%) combined with solar (10.88%), onshore wind (0.30%), and batteries (3.70%) are able to maintain the reliability of the system.

Although the LCOE of RE is relatively cheap, the investment cost (per MW nominal capacity) of some RE technologies can get more attention. The investment cost of hydro, biomass, and onshore wind power plants is more expensive than that of coal, gas, and diesel power plants as presented in **Chapter 4.1.3.** Solar PV is the only RE technology that has a cheaper investment cost than coal and gas power plants. This can be a deciding factor when the upfront budget is limited. Nevertheless, based on the optimization results, the cost-optimum 2050 system still has a smaller levelized capital cost compared to that of the 2021 system i.e. 0.09 and 0.10 million USD/MW respectively. This happens because solar PV accounts for 37.11% of the systemwide nominal power capacity in the emission-optimum 2050 scenario. Yet, it should also be noticed that the 2050 optimization results are based on a cost-learning assumption, in which the capital cost of all technologies in the future system is declining. Overall, as long as the system is built on the right choice of RE technologies, replacing fossil fuels with RE will potentially secure the intergenerational equity in the future Kalimantan power system.

Nonetheless, a perfect solution for the future does not exist. All energy sources produce benefits and burdens, including RE (Mittlefehldt, 2016). There are some intergenerational social challenges related to RE projects uncaptured by either the model optimizations or the interviews. For instance, the Saguling hydropower reservoir project in the 1980s in West Java, Indonesia, caused forced displacement of the local communities. However, this project is now, two decades after the displacement, considered to successfully address the injustice issue. Based on research, the resettlers are found to be satisfied with the strategic compensation that resulted in economic and social benefits from the development of aquaculture jobs in the present day (Manatunge et al., 2009). Another issue is deforestation for biomass-producing land conversions such as oil palm and pulp industrial plantations in Kalimantan which can harm people's livelihood in the long run. Therefore, the development of biomass power sources should focus on crop forests and develop neglected lands or already-damaged lands to become a reforestation process instead of deforestation (Yana et al., 2022).

Chapter 6

Discussion

6.1 Reaching zero emissions in future Kalimantan power system

6.1.1 Current and future states of fossils and renewables

Kalimantan is blessed with abundant energy resources, either fossil fuels or renewables. In terms of coal, East Kalimantan, South Kalimantan, and Central Kalimantan are Indonesia's first, third, and fourth-largest coal-producing provinces (ESDM, 2021), while Indonesia is the world's second-largest coal producer in terms of energy (i.e. 13.88 EJ) in 2020 (BP, 2021). In terms of natural gas, East Kalimantan also possesses Indonesia's fifth-largest proven natural gas reserves (Purwanto, et al. 2016) and produced 4.4 million cubic meters of natural gas in 2020 (BPS, n.d.), while Indonesia is the world's twelfth largest natural gas producer in term of volume (i.e. 63.2 million cubic meter) in 2020 (BP, 2021). While it is understandable that the Indonesian government still plans to develop a large amount of fossil power capacity in Kalimantan, at least until 2030, rapid transition to low carbon energy is necessary to fulfil the government carbon emission reduction commitment under the Paris Agreement.

Nevertheless, Kalimantan could have had a more substantial share of RE since the present day. In terms of hydropower, North Kalimantan has the second largest hydropower potential in Indonesia, while a combination of East Kalimantan, South Kalimantan, and Central Kalimantan has the third-largest one and West Kalimantan has the fifth largest one (ESDM, 2019). In terms of solar PV, East Kalimantan, West Kalimantan, and Central Kalimantan have the first, second, and third-largest solar PV potential in Indonesia respectively (Pragt, 2021). In terms of biomass power, Central Kalimantan, West Kalimantan, and South Kalimantan have the eighth, tenth, and eleventh largest biomass power potential in Indonesia respectively (Adistia et al., 2020). It should be noted that, as of 2021, Indonesia has 34 provinces (PLN, 2021). However, most of these technical potentials do not yet delineate the spatial constraints related to the existing high-voltage grid network or local (indigenous) communities.

6.1.2 Necessity of coal power reliance in present days

Generally, fuel prices for conventional generation such as coal, natural gas, and diesel will follow the global market price or via contract agreement between suppliers and power plant owners (IESR, 2019). While the prices of diesel and natural gas are not highly regulated, the Indonesian government has enacted a decree capping the maximum price for coal sold to power plants at 70 USD/ton (Bridle et al., 2019). This makes Indonesia has one of the lowest domestic coal prices in the world. In addition, the operating and maintenance cost of Indonesian power plants happens at the lower end of the global range, particularly due to the low cost of land and labour (IESR, 2019). These situations improve the competitiveness of coal power plants to be one of the cheapest options in Indonesia.

Establishing a power system that strongly relies on coal, accounting for 68% of the electricity generation mix in 2021, in Kalimantan is justifiable. Firstly, Kalimantan produces Indonesia's largest amount of coal on its own land. This provides security of supply for coal power plants in Kalimantan, considering their prominent role as baseload power. Secondly, Kalimantan has one of the lowest electrification ratios in the western part of Indonesia, with Central Kalimantan did not even reach a 90% electrification ratio in 2021 (PLN, 2022). Thirdly, the Kalimantan power service was far from being reliable, having frequent rolling blackouts in many grid-connected areas. Expanding the capacity of coal power plants in the last few years has helped tackle this issue for the most part. Fourthly, as of 2021, around 4-6% of Kalimantan residents still live in poverty, although this number is still below the national average of around 9% (BPS, n.d). Providing affordable, reliable electricity services to consumers with cheap, stable coal energy is then the most optimum solution from technological, economic, and social perspectives in the present day.

Nevertheless, coal is currently considered the dirtiest source of energy in terms of environmental impacts. Coal power plants generally produce 849 $\mathrm{kg_{CO2eq}}$/MWh, much larger than diesel (600

kg_{CO2eq}/MWh) and natural gas (433 kg_{CO2eq}/MWh) counterparts (Quaschning, 2021). Based on the cost-optimization model, Kalimantan's coal-dependent power system produces 682 kg_{CO2eq}/MWh in 2021. It only declines slightly to 515 kg_{CO2eq}/MWh in 2030 if the electricity generation mix still follows the current plan according to RUPTL PLN. This happens because coal still accounts for more than half of the mix in 2030, despite the rising share of RE. Moreover, the rapid expansion of coal mining activities in Kalimantan has brought about other environmental issues such as deforestation and overlapping land claims. This situation is aggravated by the fact that closed coal mines are rarely being rehabilitated due to weak reinforcement of specific regulations (Atteridge, et al. 2018). As climate change issues are becoming more prominent, phasing out coal power plants, including the other fossil power plants, turns out to be one of the most important steps in the energy transition.

6.1.3 Sound path to wean away from fossil fuels

Superseding fossil fuel power plants with RE counterparts to achieve the zero-emissions target is substantial and attainable. Based on the cost-optimum baseline scenario, the plunging share of coal, gas, and diesel in the generation mix from 67%, 14%, and 8% in 2021 to 6%, 4%, and 0% in 2050, respectively, will also plunge the emission level from 682 to 18 kg_{CO2eq}/MWh. In the meantime, the Indonesian government still considers coal and natural gas power plants in future projects (PLN, 2021). However, the complete omission of fossil fuel power plants in the mix is possible, resulting in a zero-emissions level in the 2050 emission-optimum configuration. Considering coal and natural gas power plants have different roles in the power system, the former being baseload power while the latter being peaking power, determining the right choices of renewables to replace them is therefore critical.

6.1.3.1 **Hydropower: from baseload to peak**

The optimization results of all model scenarios show that hydropower will potentially become the cornerstone of the Kalimantan power system in 2050. Be it baseline or emission optimum solution, either flatter or steeper demand deviation, hydropower plays a pivotal role in having the largest share in the 2050 electricity generation mix. Even when its maximum potential capacity is halved in the sensitivity analysis, it is still capable to be the backbone of the power system. Kalimantan being blessed with an enormous amount of hydropower potential is one of the main reasons. And hydropower being the cheapest option of power plants in terms of LCOE in all modelling scenarios is another reason. Despite requiring a rather expensive investment cost, its LCOE becomes so low partly due to its low variable cost and long lifespan, 50 years in the model and up to 90 years in real life. Meanwhile, the lifespan of the other type of power plants is usually in the range of 20-30 years. Lastly, another important reason is that hydropower is capable to provide electricity generation from baseload to peak (Danish Energy Agency, 2021).

There are two main types of hydropower plants i.e. reservoir and run-of-river in which both types are aggregated into a single type of hydropower plant in the model. Run-of-river hydropower is dispatched for baseload power, while reservoir hydropower has more flexibility in its electricity generation. To utilise its flexibility the most, reservoir and run-of-river hydropower plants can be combined in cascading river systems. In cascading river systems, the energy output of run-of-river hydropower plants can be regulated by an upstream reservoir. This extends the functionality of hydropower systems to meet both baseload and peak demand as well as become energy storage in the reservoir (Danish Energy Agency, 2021). Therefore, the flexibility of this kind of system can be essential to provide a reliable electricity supply from baseload to peak in a RE-dependent power system.

The most recent and largest hydropower project in Kalimantan is planned to establish the cascading system. This project, planned to be commissioned by 2026, will consist of five hydropower plants with different respective capacities and be located along the Kayan River, North Kalimantan, with a total nominal capacity of 9 GW. This project has a total investment of 17.8 million USD (Government of North

Kalimantan, 2021). The nominal capacity of this project is even larger than that of North Kalimantan in the 2050 emission-optimum scenario i.e. 2 GW but still lower than the maximum hydropower potential in North Kalimantan i.e. 21 GW as presented in **Figure 37**. Therefore, it illustrates that the optimized hydropower capacity in the emission-optimum scenario can be considered both technically and economically feasible in real life.

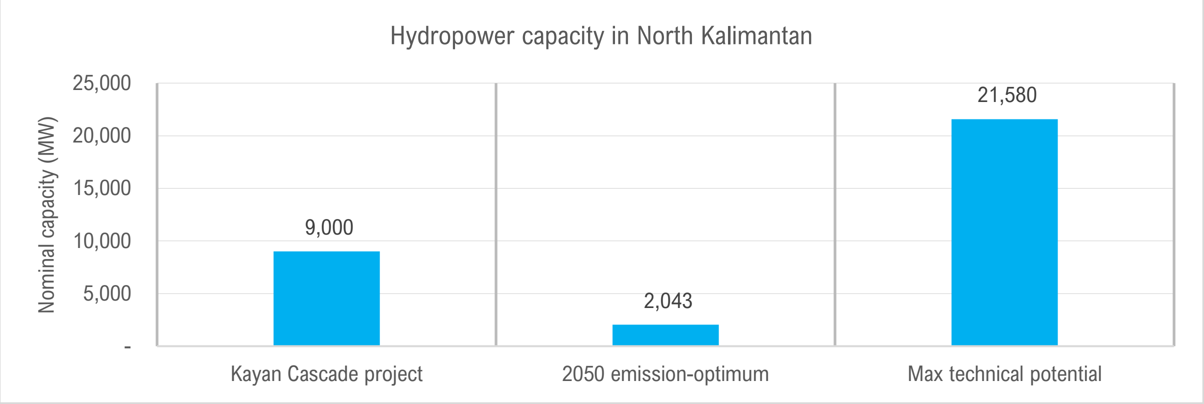

Figure 37 Comparison of nominal capacity between the actual Kayan Cascade project, hydropower in the 2050 emission-optimum scenario, and maximum technical potential of hydropower in North Kalimantan.

Nonetheless, according to a news report, the Kayan Cascade project is being delayed due to land use permit and regulation issues. Another issue faced by this project is that this project requires at least two local villages to be displaced. Currently, these villages do not have access to PLN electricity service because the current power grid network does not reach this region (Pratama, 2022). Ironically, these unelectrified communities will be displaced to establish access to PLN electricity service. This situation creates a double-edged sword in terms of intragenerational equity. While the electricity access to the grid is improved, the displaced communities, which are often the most vulnerable groups, might lose their livelihoods that depend on the particular rivers or forests. Therefore, while the techno-economic prospect is evident, the social aspect should also be taken into account to ensure successful RE projects.

Furthermore, too much reliance on hydropower may also be an issue related to energy justice. Based on the 2050 emission-optimum scenario, hydropower accounts for around 76% of the Kalimantan electricity generation mix. It makes the power system relies heavily on this technology. For instance, Brazil, which around 59% of its electricity generation comes from hydropower by 2014 (Statista, 2016), experienced an energy crisis in 2014 as a result of a lack of water in the reservoirs due to severe drought events (Hunt et al., 2022). Therefore, to address this availability issue in the future, Hunt et al. (2022) suggested hydropower cascading systems should operate with a low capacity factor of 50%. This low capacity factor will allow hydropower to increase its generation during the absence of the other electricity generation such as solar and wind. However, having low capacity factor might also result in a higher LCOE, which might affect affordability of the electricity service in the future. Considering that, in the 2050 emission-optimum scenario, the systemwide hydropower in the model operates at around 93% capacity factor.

6.1.3.2 Retrofitting coal with biomass

The entire Kalimantan in general possesses an enormous amount of both coal and biomass resources. East Kalimantan, South Kalimantan, and Central Kalimantan, the largest coal-producing provinces in Kalimantan, are estimated to have significant biomass potential for power generation (Dani & Wibawa, 2018; IESR, 2019). One of the reasons is that South Kalimantan, Central Kalimantan, and East Kalimantan are also among the largest oil palm and wood producing provinces (Xu et al., 2020; Simangunsong et al., 2017). Currently, most biomass power plants in Kalimantan use oil palm waste as their main fuel (Siagian et al., 2021). In addition, these provinces are blessed with arable lands that can support the development of massive industrial forest plantations for biomass resources (Simangunsong et al., 2017).

Early phasing out of existing coal power plants can be a necessary step toward the 2050 net-zero emission target. If no new coal power capacity is added between 2031-2050, the remaining coal power capacity in Kalimantan is estimated to decline from 2,485 MW in 2021 to 614 MW in 2050. Meanwhile, based on the cost-optimum baseline scenario, the cost-optimum Kalimantan power system only needs around 264 MW of coal power capacity. On the other hand, biomass power plants can potentially replace the role of coal power plants for baseload. In the emission-optimum scenario, the share of biomass in the electricity generation mix grows from 0.85% in 2021 to 9.49% in 2050 in exchange for the complete phase-out of coal power plants. This includes the soaring increase of biomass power capacity from 41 MW in 2021 to 856 MW in 2050

Nonetheless, phasing out coal power plants prior to their end of life is both costly and impractical (KLHK, 2021). To address this issue, the existing coal-fired power plants can be completely retrofitted into biomass-fired power plants. Based on the 2050 optimization results as mentioned in the previous paragraph, the remaining coal power capacity in the baseline scenario is still lower than the biomass power capacity needed in the emission-optimum scenario where coal is completely phased out. The remaining coal power capacity in 2050 is also located in the same province as the biomass power capacity in the emission-optimum configuration i.e. South Kalimantan, Central Kalimantan, and East Kalimantan. This indicates the potential path of coal-to-biomass retrofit in the future Kalimantan. The comparison between coal and biomass capacity within South Kalimantan, Central Kalimantan, and East Kalimantan in different scenarios is presented in **Figure 38.**

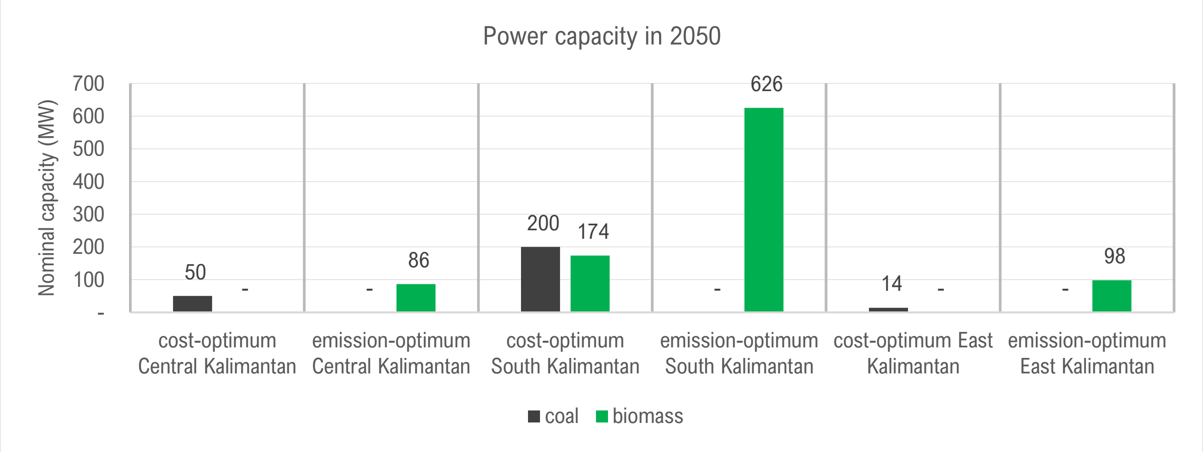

Figure 38 Comparison of nominal power capacity between coal and biomass power plants in different 2050 scenarios within South Kalimantan, Central Kalimantan, and East Kalimantan.

There are a number of coal-to-biomass projects in the world that demonstrates the feasibility of coal-to-biomass retrofit. One of the largest projects is the Avedøre Power Station (757 MW of capacity) in Denmark, going from retrofitting one coal power unit into a biomass one in 2016 to becoming a 100% biomass power plant in 2023. Its primary biomass resource is wood pellets from forestry and sawmills (Ørsted, n.d.). Retrofitting existing power plants can also be advantageous as it can potentially reduce the large upfront costs to build new biomass power plants. A lower upfront cost may further result in a lower LCOE of biomass so that biomass can be more competitive.

Phasing out coal power plants in the future will also affect the fate of coal mines in Kalimantan. However, closed coal mines will not go abandoned. Coal mine reclamation for biomass plantations has been being studied in recent years. Beechwood cultivation, among other types of woods such as burflower-tree and raintree, for coal mine reclamation is estimated to be one of the most potential solutions, particularly in Kalimantan. Considering that wood pellet produced from beechwoods is considered one of the best fuels for biomass power plants due to its high calorific value and low moisture content. However, determining which biomass resources to develop depends on the type of technology of the existing coal power plants (Siagian et al., 2021).

Nevertheless, the transition away from coal does not always provide justice to everyone in the Kalimantan power system, especially related to intragenerational equity on how benefits and burdens are to be distributed. Coal miners are often affiliated with the vulnerable groups. The main reason coal miners work at coal mines in Kalimantan is to move away from poverty (Albertus & Zalukhu, 2019). According to Baran et al. (2020), a study in Poland, a large coal-producing country, suggests that half of the ex-coal workers failed to move to other sectors and eventually left the labour market. One of the reasons is the lower education level of coal miners relative to other sectors. Thus, they are unable to move to green or neutral sectors and the energy transition might create a net loss of labour from the macroeconomic perspective.

There are a number of discussion related to what jobs in the other sectors are suitable to coal miners after coal jobs disappear. According to Pai et al. (2020), recent policy debate and academic research suggest that coal miners can migrate to renewable jobs such as solar PV or wind farms. Their research suggest that solar PV jobs could be techno-economically suitable to provide job replacement for ex-coal workers. However, considering the number of coal workers in coal mine activities, a huge scale of installed solar PV capacity would be required per coal mining area to absorb mining jobs. Their research then stated that, in practical terms, not all ex-coal miners might be able to migrate to solar PV jobs locally. This argument can be relevant with the energy transition in the Kalimantan power system because, based on the optimization result, solar PV might only contribute to 11% of the electricity generation mix in the 2050 emission-optimum scenario. Therefore, the energy transition in Kalimantan should be able to address this issue by assuring available jobs, either green or neutral jobs, to ex-coal workers to improve justice for the vulnerable groups while achieving net-zero emissions in the power system.

6.2 Limitations on methodology and results

6.2.1 Reliability under nature’s uncertainty

The model developed in this research assumes that dispatchable renewable power generators do not suffer from supply variability. In real life, dispatchable renewable power generators such as hydro and biomass also have issues related to their availability throughout the years. These issues become the limitations this research does not capture.

6.2.1.1 **Uncertainty of hydropower flexibility**

Being located on the equator, Kalimantan experiences seasonal variation between wet and dry seasons. Wet season happens approx. from October to March, while dry season happens approx. from April to September. The seasonal variation results in lower hydropower potential during the dry season and vice versa. Overall, the dry to wet season ratio of total available energy for hydro is 42:58 in Kalimantan (Agung Wahyuono & Magenika Julian, 2018).

Although the dry-to-wet season ratio cannot tell about the situations of specific rivers and reservoirs in Kalimantan, it can indicate that the difference in hydropower availability affected by the seasonal variation has the potential to affect the electricity generation mix to a certain extent. The sensitivity analysis is conducted by assuming a situation with different water availability. Based on the sensitivity analysis, halving the maximum hydropower potential in Kalimantan slightly shifts the share of hydropower in the emission-optimum electricity generation mix from 75.64% in the original hydropower potential to 74.13% in the halved hydropower potential. This result indicates that hydropower might be less flexible in generating electricity for peak demand in real life because its capacity might only be sufficient to supply baseload during dry season. However, the sensitivity analysis still does not consider the exact seasonal variation due to limited data availability.

A more considerable issue related to hydropower generators is drought. The Indonesian archipelago is prone to get affected by El Niño where the precipitation level drops significantly during the event. For instance, during one of the strongest El Niño events that happened in 2015, around 80% of all hydropower reservoirs in Indonesia suffered from a water level deficit from May to July that resulted in a water crisis for power and irrigation (Harsoyo et al., 2015). This could create a conflicting justice issue when deciding whether to use the limited water for energy security or food security. A more extreme situation occurred in PLTA Riam Kanan, a hydropower reservoir in South Kalimantan. No single rainfall occurred between July and September 2015 in its catchment area (Harsoyo et al., 2015). El Niño event itself occurs every two to seven years at irregular intervals (NOAA, 2021). Therefore, RE-dependent power system planning in Kalimantan should also anticipate the water resource variability during this kind of meteorological events.

6.2.1.2 **Uncertainty of biomass availability and consideration of social impacts**

The issues suffered by hydropower may also affect the availability of the other dispatchable renewable power generators such as biomass. Dry years may lead to a drought that may lead to a lower crop harvest. There are two common implications when this situation happens. First, there will be a problem on the supply side of biomass power plants. Second, the flexibility of hydropower reservoirs is contracted because the lower water level in the reservoirs may be distributed more for irrigation purposes. The hydropower plants can still generate electricity when the water flows downstream, but it becomes less flexible in terms of ramping capability since the water flow is constrained by the amount of water needed for irrigation (Jurasz et al., 2020). All optimization scenarios do not incorporate this variability of biomass. Nevertheless, it can be observed in the sensitivity analysis that halving the maximum biomass potential in Kalimantan slightly reduces the share of biomass in the mix from 9.49% to 8.67%. It means the variability of biomass availability has the potential to still be manageable because the maximum biomass potential is significantly larger than needed.

Biomass availability during normal years is another issue to consider. Currently, most biomass sources in Kalimantan come from waste from the oil palm and wood industries (Dani & Wibawa, 2018). In 2021, the capacity of biomass power plants in Kalimantan is only 41 MW. Substantially more biomass resources other than waste may be needed to meet the biomass demand for 856 MW of capacity based on the 2050 emission-optimum scenario. Although not as erratic as solar and wind, biomass supply also has a problem related to intermittency. The intermittency is related to the difficulty in coordinating the logging, chipping, trucking, storing, and burning of biomass materials with the demand for power plants (Mittlefehldt, 2016). Furthermore, many biomass resources come from non-energy industries such as food, paper, and lumber.

There is a concern that a major increase in the use of forests and agricultures for fuels may negatively affect available supplies of these materials which in turn drives prices up (Mittlefehldt, 2016). This may lead not only to the biomass fuel price fluctuation but also to social issues related to food and household goods prices, in which the low-income groups may suffer the most. Meanwhile, the energy transition in Kalimantan should help tackle the social injustice issues related to energy provision without adding more social issues. Therefore, biomass supply variability in RE-dependent power system planning needs to be taken into account.

6.2.2 PHES as an energy storage option

While lithium-ion batteries can be developed in many regions due to a low geographical constraint, PHES that has a higher geographical constraint can also be developed in Kalimantan due to its large potential. According to Silalahi et al. (2022), the most productive groundwater basins, which are potential to be the initial reservoir fill, are located in Kalimantan, incl. several other Indonesian islands. In total, Kalimantan has the PHES technical potential of 64 TWh. The advantage of PHES compared to lithium-ion batteries is that it is capable to store relatively larger amount of energy for longer periods (Silalahi et al., 2022). Therefore, the inclusion of high spatial resolution of PHES potential sites in the optimization model might result in different share of intermittent RE with low variable cost such solar and wind due to the PHES aforementioned capability and different spatial characteristics with respect to the energy regions in the model compared to lithium-ion batteries. Nevertheless, the high spatial resolution of PHES potential sites data in Kalimantan are currently not available.

6.2.3 Spatially-bounded RE vs. spatially-bounded grid

The model does not include the exact spatial locations of future power plants. It means that every new power capacity added in each energy region will cost the same based on its type regardless of whether it needs to build a new transmission line in real life or not. Therefore, possible new transmission cost for connecting new plants with the existing high-voltage grid is ignored. In real life, the existing high-voltage grid in Kalimantan is spatially-constrained, while some new power plants, especially renewables, may be located away from the grid to a certain extent.

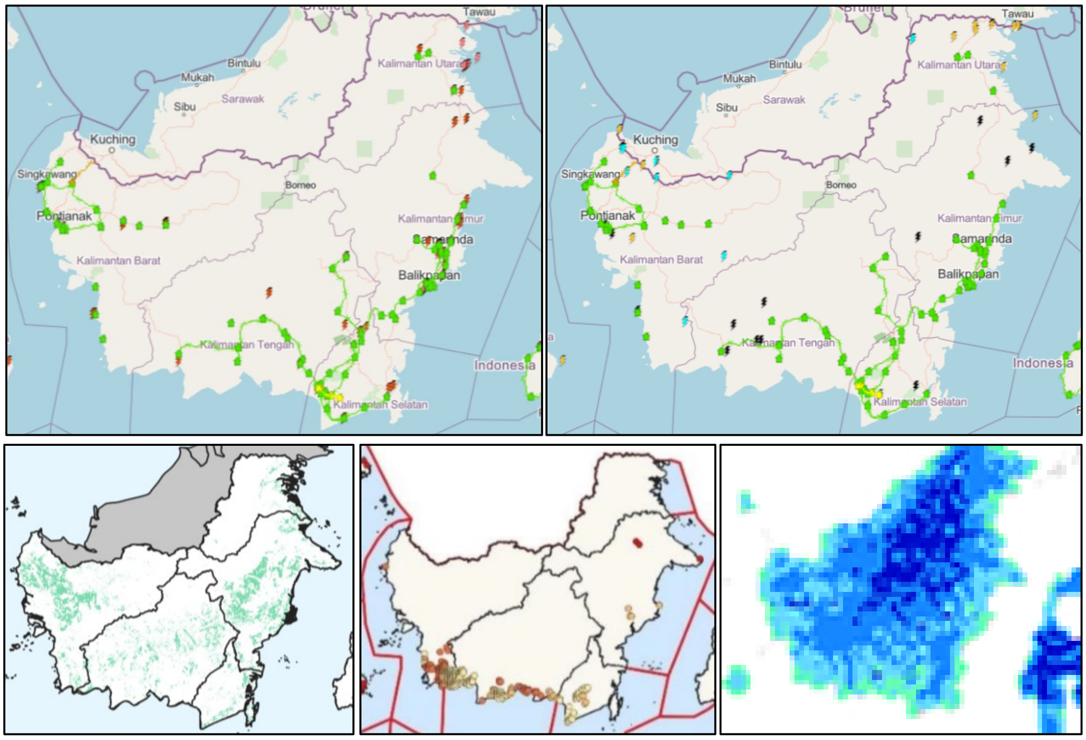

Figure 39 Comparison between the high-voltage transmission network (top: green lines), high-voltage substations (top: green), power plants: coal (top left: red); gas (top left: pink); biomass (top right: black); solar (top right: yellow); hydro (top right: blue), and RE potential sites: solar (bottom left: turquoise), onshore wind (bottom middle: coloured dots), hydro (bottom right: shades of blue, darker means higher potential and vice versa) in Kalimantan. Source: ESDM (2022); Pragt (2021); Simanjuntak (2021); Hoes et al. (2017).

Figure 39 illustrates the comparison between the high-voltage transmission network, power plants, and RE potential sites in Kalimantan. It can be seen that most of the transmission lines are located alongside the coastal regions. Most existing coal, gas, and biomass power plants are located alongside the current high-voltage transmission lines, while most existing hydro and solar PV power plants are located at a farther distance. It happens because the formers are relatively spatially-flexible. Fortunately, many potential sites for solar PV and onshore wind are alongside or close to the existing network. Furthermore, these potential sites already consider spatial constraints related to social issues such as residential, agricultural, and protected lands. Considering their power capacity in the 2050 emission-optimum scenario is far smaller than their respective maximum potential, their integration in the current grid can be relatively easy and less costly because the chosen location can follow the closest ones to the grid. Although, possible new transmission costs should still be taken into account.

Nonetheless, the most potential sites for hydropower are located relatively much farther from the grid. This situation may require some extra costs in building hydropower plants, indicating that the LCOE of hydropower is possibly not as cheap as that from the model optimization. Due to limited data availability, the model conceptualization for hydropower potential also overlooks the possibility of community displacement related to spatial constraints. As discussed in **Chapter 6.1.3.1**, for instance, the actual large-scale hydropower project in Kayan River requires at least two local villages without PLN grid connection to be displaced because the chosen potential site coincides with local residential areas. It also requires PLN to build new transmission lines to connect this rural area with the existing grid.

6.2.4 Uncaptured off-grid systems

The optimization model developed in this research assumes that the electricity demand from all Kalimantan residents in the future is grid-connected. However, the actual PLN grid expansion by 2050 may not be able to reach all rural communities in Kalimantan. For instance, a village named Long Berang in Malinau, North Kalimantan has no PLN grid connection in the present because it is located faraway upstream that currently can only be reached via the river using boats for 4-5 hours from the city (Pranitha & Lubis, 2018). The lack of fundamental infrastructure such as land transportation creates some difficulties for the government to expand the grid to reach this kind of regions in Kalimantan. Meanwhile, justice has become one of the pillars in the LTS-LCCR 2050, which means an equal access to electricity service for all residents needs to take into account.

The Indonesian government has passed regulations and implemented several programs to accelerate rural electrification that focuses on remote areas, underdeveloped border regions, and inhabited small islands with off-grid RE systems. These incentivise IPPs to participate in rural electrification, including an access to a government subsidy (Setyowati, 2021). In return, it helps provide an electricity access to rural areas using renewables without the urge to expand the high-cost PLN grid network to rural areas with severe geographical limitations in the near future.

The inclusion of off-grid systems in the optimization model may result in significantly different systemwide electricity generation mix in future Kalimantan. It is mainly because of different spatial and economic characteristics between hydro, biomass, solar, and wind power that may or may not be compatible with micro-scale off-grid systems. For instance, many solar PV potential sites are located in rural regions, while most wind potential sites are located in coastal regions nearby the existing grid as shown in **Figure 39.** Moreover, the investment cost of solar PV is the lowest among the other technologies. Furthermore, according to Veldhuis & Reinders (2015), the LCOE of a stand-alone off-grid PV system, particularly in West Kalimantan and Central Kalimantan, is up to 30 USD/MWh lower than that of diesel-based off-grid system that is commonly used in present Kalimantan. Pranitha & Lubis (2018) also shows that a stand-alone off-grid PV system equipped with lithium-ion battery storage can fulfil the demand in Long Berang village for four days with a lower cost than using a diesel-based off-grid system. Therefore, the share of solar PV in the mix would potentially be higher than that in the optimization results if off-grid systems are conceptualized in the 2050 Kalimantan power system model.

6.2.5 Limited groups of stakeholders

This research tries to capture how energy transition intercorrelates with energy justice in Kalimantan via power system modelling and interviews. The energy transition should be able to address the injustice issues present within all stakeholders, ranging from public and private sectors to local residents. The interviews help validate the conceptualized model and optimization results so that the results can provide useful insights related to techno-economic potential and energy justice. However, the stakeholders being interviewed cannot capture all involved groups due to the limited number of interviewees and the temporal limitation of this research.

Firstly, none of the interviewees comes from the most vulnerable groups, either low-income groups or rural communities. Although, ID03 has several information related to the situation in some rural households due to her close relationship with some rural residents. These groups currently suffer injustice issues in many aspects such as supply availability, equity in access, and affordability. Many of them either do not have electricity access or do not have electricity access from off-grid private diesel generators. ID07 mentioned that private diesel generators are included in the electrification ratio data made by the government, resulting in data inaccuracy. Meanwhile, the model does not take into account this issue as all diesel power capacity provided in the data is aggregated as grid-connected diesel power plants and able to run at any timestep due to limited open data. Howbeit, their perception of the current power system and the energy transition would be important to better associate the model with energy justice parameters.

Secondly, none of the interviewees comes from North Kalimantan. This province lacks available data since it just became a separate province in late 2012. Several official reports and scientific papers related to RE potentials or electricity demand do not include North Kalimantan as a separate province. Furthermore, based on the ESDM Geoportal, this province has no grid interconnection to the other provinces in the present day. At the same time, it has the largest hydropower potential in off-grid rural areas. There is a lack of high spatial resolution data regarding the hydropower potential sites that may coincide with local communities. Furthermore, all found references also stated that this province has zero biomass power potential without further explanation, while that of the other Kalimantan provinces is abundant. Therefore, potential information from interviews could have been essential.

Lastly, none of the interviewees has a background in Kalimantan's private sector or RE IPP in Kalimantan. Based on the interview, ID01 mentioned that an employer of one of his family members needed to pay a more expensive tariff than what has been regulated because PLN needs to build a new transmission line to connect their factory with electricity. Since new transmission cost related to the spatial distance of new power plants is not considered in the model, the information related to this issue could have been useful to provide insights about to what extent the spatial location of RE integration may affect the costs and electricity service access. Also, considering that many RE potential sites are located away from the grid that may open access to rural grid-electrification.

6.2.6 Compatibility between the optimization model and intra- & inter-generational equity

The optimization results capture some energy justice parameters in a considerable extent i.e. affordability and availability, while the other parameters are less captured i.e. intra- and inter-generational equity. There are several reasons behind this issue. Firstly, the optimization model does not conceptualize the electricity access with respect to residential areas due to its relatively low resolution and lack of related constraints. Secondly, the optimization model does not include off-grid systems which in turn could overlook the necessary electrification in the regions far away from the grid. Lastly, the optimization model cannot evaluate the intergenerational changes beyond grid-connected system costs and system availability. For instance, it cannot demonstrate spatial (e.g. land use) changes that may affect people's livelihood due to the massive development of RE in Kalimantan. Furthermore, it also cannot demonstrate macroeconomic changes that might significantly impact on the socio-economic situation affected by massive RE integration in the future.

6.2.7 Cost assumptions

The LCOE obtained from the optimization results is highly affected by the cost assumptions used in the model. The most prominent issue in this case is the LCOE of hydropower. The LCOE of hydropower is significantly lower than the LCOE of the other power plants. It is 20 USD/MWh in 2021 and declines even more to 15 USD/MWh in the 2050 emission-optimum scenario. According to ASEAN (2016), the LCOE of hydropower in ASEAN countries is ranging from 19 to 85 USD/MWh, where Indonesia has the second lowest LCOE behind Myanmar. Meanwhile, the average LCOE of hydropower in Indonesia is 33 USD/MWh.

Hydropower LCOE is highly sensitive to capital costs and capacity factor (ASEAN, 2016). Considering that newer hydropower projects in Kalimantan are possibly located in isolated areas with none-to-minimum road infrastructure, the capital costs of this kind of project can be larger than the capital costs conceptualized in the model. Moreover, its capacity factor from the optimization result is very high i.e. 85% in 2021 and 93% in 2050. Although the maximum hydropower capacity factor can be up to 95% (Danish Energy Agency, 2021), the actual hydropower capacity factor in Indonesia is ranging from 50% to 85% (ASEAN, 2016). Therefore, the hydropower LCOE in actual Kalimantan power system has the possibility to be larger than that of the other technologies such as solar PV or biomass, which then affects the most-optimum economic dispatch in the Kalimantan power system.

Chapter 7

Conclusion and Recommendation

7.1 Conclusions

7.1.1 Answering the main research question

This research is intended to answer the main research question: "What is the optimum configuration of renewable energy integration in the interconnected Kalimantan power system in 2050 to achieve net-zero carbon emissions while considering some energy justice parameters?" Based on the optimization and energy justice analysis of the energy transition in the Kalimantan power system, it concludes that RE integration in the interconnected power system will lower the levelized system costs in 2050. This impact includes achieving net-zero carbon emissions and improving energy justice in terms of affordability, availability, and intra- and inter-generational equity in the Kalimantan power system.

There are a number of conditions to fulfil so that the positive impact of RE integration and transmission system interconnection in the Kalimantan power system can be achieved. Firstly, the majority share of renewable power capacity comes from the dispatchable, low-cost RE technology in Kalimantan i.e. hydropower. Secondly, the other renewables such as biomass, solar PV, and onshore wind, equipped with lithium-ion batteries, are developed in areas where the hydropower potential is relatively low. Thirdly, fossil power capacity should be phased out completely by 2050. Fourthly, the transmission system interconnection should accommodate grid connections to potential RE sites in rural areas in Kalimantan. Lastly, the demand fluctuation between off-peak and peak hours should not be too steep or too unpredictable to keep the system cost low.

7.1.2 Reflection on the research limitations

Nevertheless, this research has several limitations. First, the actual demand profile of Kalimantan is not openly available. Better stakeholder engagement would be beneficial to gain access to crucial data. Second, the spatial resolution of some RE potential data such as hydro and biomass is lower than that of solar and wind. Resolution consistency of input data would be necessary to provide useful results. Third, the variability of dispatchable renewable such as hydro and biomass is not taken into account. It would be important to avoid overestimation of their capability in order to ensure system reliability in real life situations. Fourth, some other available technologies such as PHES are not included in the model. PHES inclusion may stimulate larger share of intermittent RE in the mix due to its larger and longer storage capability. Lastly, the model optimization and interviews cannot capture a number of important things such as rolling blackouts in some specific regions, unmet demand from low electrification ratio, and the perception of the most vulnerable groups that can be import for capturing all energy justice elements. These things would be substantial to help better analyse the impact of energy transition on energy justice.

7.2 Policy recommendations for the Kalimantan power system

Based on official documents and the interview with ID05, the Indonesian government plans to still include fossil fuels such as coal and natural gas in the 2050 electricity generation mix. In LTS-LCCR 2050, coal and natural gas will account for 38% and 10% of Indonesia's electricity generation mix, respectively, while RE will account for 43%. To manage the CO_2eq emission level, the government plans to equip 76% of the coal power plants with CCS. By that plan, it is estimated that the emission level will be 104 kg_{CO2}/MWh (KLHK, 2021). This plan also includes the power grid expansion to some rural regions in West Kalimantan and North Kalimantan and the interconnection between all Kalimantan provinces (PLN, 2021). The development plan of smart micro grids for rural areas to support the integration of variable RE in rural areas is also emphasized (KLHK, 2021). Moreover, ID05 mentioned that the government has no plan to annul the coal price cap policy for the energy transition.

Howbeit, this policy might underutilise the ample potential of RE in Kalimantan. Furthermore, it does not specify how the power system in each province will appear. Setting aside the power systems in the other Indonesian regions, the optimization results indicate that the Kalimantan power system has the potential to reach beyond the RE target set by LTS-LCCR 2050, achieving zero emissions with an accessible, affordable, reliable system while addressing energy justice. Therefore, this research provides several policy recommendations as presented in **Figure 40**.

Fossil fuels

- Phasing out coal power plants completely by 2050
- Phasing out natural gas power plants completely by 2050

Renewables (technology)

- Developing cheap hydropower as the primary source of the power system
- Retrofitting newer coal (incl. natural gas) power plants into biomass (incl. biogas) power plants gradually
- Developing less-intermittent solar PV equipped with lithium-ion batteries

Renewables (location)

- Developing large-scale hydropower cascade systems mainly in upstream regions of West Kalimantan and North Kalimantan
- Developing smaller-scale hydropower plants mainly in East Kalimantan, South Kalimantan, and Central Kalimantan
- Developing reforestation for biomass power resources mainly in South Kalimantan
- Developing coal mine reclamation conversion into biomass power resources mainly in South Kalimantan, Central Kalimantan, and East Kalimantan
- Developing utility-scale solar PV farms equipped with ample lithium-ion battery capacity mainly in Central Kalimantan, South Kalimantan, and East Kalimantan
- Developing onshore wind farms mainly in coastal regions of Central Kalimantan to complement solar variability

Demand

- Implementing demand-side management that can lessen the deviation between off-peak and peak demand to help reduce the system costs and tariffs

Justice

- Minimizing the development of biomass resources that conflict with non-energy use (foods, household goods, etc.) and land use by maximizing the utilisation of biomass waste from abundant oil palm plantations and by developing reforestation.
- Expanding power grid networks to the communities in rural areas that coincide with the potential RE sites such as solar, hydro, and biomass to improve the grid-connected electricity access.

Figure 40 Policy recommendations based on the analysis result

7.3 Future research recommendations

Based on the insights, conclusion, and limitations of this research, there are three research avenues to be explored as follows.

7.3.1 High-spatial and high-temporal hydro and biomass potential research

High-spatial hydro and biomass potential will be useful for exploring where the hydro and biomass potential sites are specifically located. Furthermore, high-temporal hydro and biomass potential will be useful for exploring the variability of hydro and biomass resource availability within the same year and between different years. It then explores which sites are feasible to develop based on technological, economic, and social constraints. This data can be important for power system modelling with high RE integration, either variable or dispatchable, so that it is capable to provide output that can observe the impact on the development of power grid networks and resemble real-life supply dynamics. This research can also include the analysis of high-spatial and high-temporal HPES.

7.3.2 Incorporating the most vulnerable group in RE development in qualitative analysis

The most vulnerable group such as indigenous communities and households below the poverty line is the most affected group by the energy injustice present in the current Kalimantan power system. While the development of RE shows a promising potential to address energy justice on the system level, its critical impact on the most vulnerable groups in terms of energy justice is often overlooked. The systems modelling approach is not capable to incorporate this level of detail. Therefore, qualitative analysis can be implemented to incorporate this group in the development of RE in the Kalimantan power system in order to assure the positive impact of the energy transition on energy justice.

7.3.3 Macroeconomic and land-use simulation for techno-socio-economic assessment

System dynamics modelling used in this research can optimize the economic dispatch of the power systems but cannot extensively incorporate the impact of RE integration on energy justice which is strongly related to macroeconomic situations and diverse human perspectives such as conflicting land use or job availability. An analysis using simulation models that capture these elements can be conducted to assess the impact of regional or national energy policy changes on the economy, society, and environment on a macro level. The simulation models also capture highly-spatial land-use simulation to assess whether the development of spatially-bounded RE may conflict with residential areas or other important ecosystems. Considering that the rapid growing Kalimantan population in the future could require extensive development of residential areas that coincide with the most potential sites of RE mentioned in the previous chapters. This research is useful to determine future policies related to the technical development of RE and its socio-economic impact.

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