Exploring the feasibility of inter-island transmission interconnection in Indonesia

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Exploring the feasibility of inter-island transmission interconnection in Indonesia

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TU Delft

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Enjoy the read! For any questions, you can always reach out to me through: maartjevanasselt@gmail.com.

Executive Summary

Indonesia started its journey towards a net-zero energy system. Research and developments towards these targets are currently well underway. However, present-day prediction models show that the rising demand of the island will not be met with the renewable energy technology potential. One solution for this problem is the development of power interconnections between the power systems of the Archipelago. However, short-term planning and speculations about the feasibility of inter-island interconnections block their construction. This study aims to explore the feasible options for inter-island interconnections and recommends the next steps that can be researched.

Therefore, the main research question of this study is the following:

> *"Which inter-island interconnection routes are feasible to accommodate renewable energy technology integration in Indonesia and what are the needed institutional adjustments for fostering such an interconnected system?"*

The method to answer this research question is through the combination of a techno-economical model and an institutional analysis. The techno-economical model utilizes the energy planning model 'Calliope', as the foundation of this model was already developed by researchers at TU Delft. To include geographical features, a GIS (Geographic Information System analysis) is performed and its outcomes are used to analyse the results coming from the Calliope model. The results from this techno-economical analysis are then used as input for the institutional analysis. The latter is built upon the existing Williamson framework. Due to the limited scope and timeline of this study, the aspects planning of transmission infrastructure, financing of transmission infrastructure and contractual arrangements between public and private parties are chosen as focus points in the institutional analysis.

The state-of-the-art technology used for inter-island interconnections, or submarine power cables in general, are High-Voltage Direct Current (HVDC) cables. The advantage of HVDC over HVAC (High-Voltage Alternating Current) cables is their ability to transmit power over longer distances while creating less environmental impact due to limited electromagnetic interference.

The planning of submarine power cables is a relatively new subject in academic literature. The important geographical features to consider in the design process of submarine power cable routing found in this study are the depth of water (bathymetry), seabed slope, seismic regions, and protected zones. These geographical features can be categorized in terms of their impact on the cost and risk of breakage of the cables.

This study found through a techno-economical analysis that there are multiple inter-island interconnections that are found to be needed in a Calliope power model of Indonesia and feasible considering the aforementioned geographical features. The visual shortest-path routing of these feasible cables has been determined through an AHP (Analytic Hierarchy Process), analysis combined with a Dijkstra shortest-path algorithm. The results of this algorithm can be found in the following Figure 0.1

On the institutional side of the result, this study found that there are multiple barriers that could form a barrier to the development of inter-island interconnections. The main issues found have to do with the planning, financing and contraction of the institutional side of transmission infrastructure development. In order to soothe these barriers the following recommendations are constructed; using an integrated transmission capacity planning approach, institutional strengthening for investment and creating a governance body dedicated to interconnectivity.

The conclusion of this study is that there are feasible interconnections for accommodating renewable energy technology integration in Indonesia. The found feasible routes of this methodology consist of Bali-Nusa Tenggara Barat, Kalimantan Barat-Daerah Khusus, Jakarta-Kalimantan Tengah, Jawa Tengah-Kalimantan Selatan, Jawa Timur-Kalimantan Tengah, Jawa Barat-Lampung Banten, and Kepulauan Riau-Riau and between Kalimantan Barat and Jawa Barat. Institutional adjustments are found to be crucial for fostering this interconnected system. Institutional recommendations involve integrating interconnections into the RUPTL (Electricity Supply Business Plan), strengthening foreign investment with clear policies, and ensuring transparent contractual arrangements between public and private entities. Moreover, prioritizing grid balancing and exploring sustainable financing methods like green bonds further support these efforts.

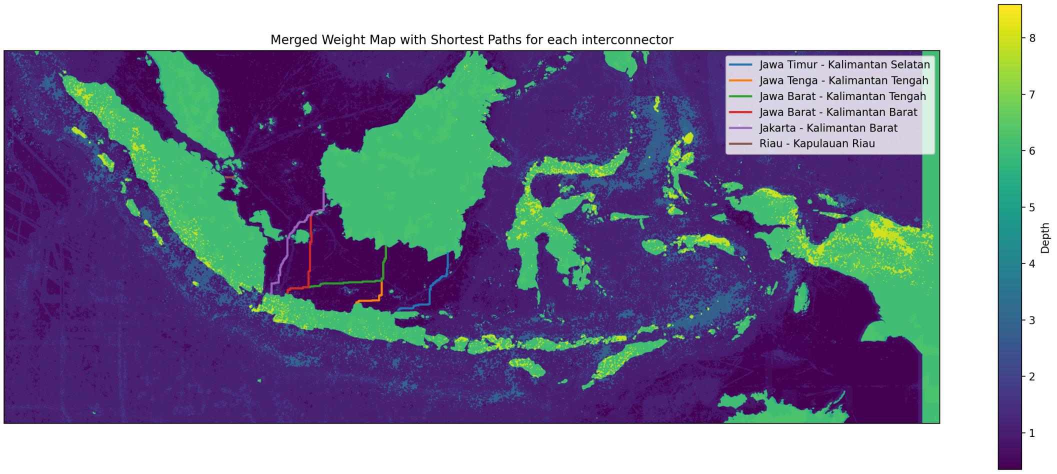


Figure 0.1: Visualisation of interconnection routes found in this study

The most important limitations of this study are the minimal use of scenarios, the use of only one energy system modelling software (Calliope) and the limited scoping for the institutional analysis. As for future research, this study invites researchers to think about the specific power flow of the system, the operational challenges, social engagement and public perception and comparison to other archipelago countries.

Contents

List of Figures

List of Tables

Nomenclature

ADB	Asian Development Bank
AHP	Analytic Hierarchy Process
BOO	Build, Operate, and Own
BOOT	Build, Operate, Own, and Transfer
Calliope	Open-source energy system modeling framework that supports the analysis and optimization of energy systems
DPR	Dewan Perwakilan Rakyat (The Parliament or House of Representatives)
EDSM	Ministry of Energy and Mineral Resources
GHGE	Green House Gas Emissions
GIS	Geographic Information System
GR	Governmental Regulation
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IESR	Institute of Essential Services Reform
IPP	Independent Power Producer
ITB	Institut Teknologi Bandung (Bandung Institute of Technology)
IUPTL	Izin Usaha Penyediaan Tenaga Listrik (Electricity Supply Business License)
MD	Ministerial Decree
MEMR	Ministry of Energy and Mineral Resources
MMAF	Ministry of Marine Affairs and Fisheries
MoEMR	Minister of Energy and Mineral Resources
MR	Ministerial Regulation
MW	Megawatt
OTEC	Ocean Thermal Energy Conversion
PLN	PT Perusahaan Listrik Negara (Persero) (State Electricity Company)
PR	Presidential Regulation
QGIS	Quantum Geographic Information System, a free and open-source Geographic Information System (GIS) software application that allows users to create, edit, visualize, analyze, and publish geospatial information and maps
RE	Renewable Energy
RET	Renewable Energy Technologies
RUED	Rencana Umum Energi Daerah (General Plan for Regional Energy)
RUEN	Rencana Umum Energi Nasional (General Plan for National Energy)
RUKD	Rencana Umum Ketenagalistrikan Daerah (General Plan for Regional Electricity)
RUKN	Rencana Umum Ketenagalistrikan Nasional (General Plan for National Electricity)
RUPTL	Rencana Usaha Penyediaan Tenaga Listrik (Electricity Supply Business Plan)

1 Introduction

1.1 Global energy transition

The use of fossil fuel generators for electricity and heat production contributes significantly to *Global Greenhouse Gas Emissions* (GHGE), which in turn cause a rise in Earth's temperatures, altering weather patterns and disrupting the natural balance of the environment [United Nations, a]. To mitigate these negative effects of human-induced climate change, the world is currently undergoing an energy transition, shifting from fossil-based to renewable-based electricity generation that does not emit GHGE. However, this transition is a massive and complex process that presents new challenges [Renewable Energy Agency, 2022].

One such challenge is the design of the power system, which is responsible for the flow of electricity from generation to the end-user. Research indicates that incorporating renewable energy technologies (RET) into the existing power system creates balance problems. The power system operates by maintaining a constant frequency, which is determined by the supply and demand of power at any given time. Fossil fuel generators can be regulated to maintain this balance, but the supply from RET cannot be controlled as it relies on the availability of sources such as solar or wind energy at any given moment. Since we cannot control the weather, smarter methods are required to maintain the frequency of the power grid. This makes RET power sources intermittent, meaning they are not available 100% of the time and are unpredictable [Abujarad et al., 2017].

1.2 Energy transition in Indonesia

Contributing to the world's transition to a renewable energy system, Indonesia has set the ambitious target to achieve net zero emissions by 2060 or earlier, despite being a major coal producer and user. The country even sees economic opportunities in this transition and has implemented policies and frameworks towards its goal of becoming a renewable-fueled economy [International Energy Agency, 2020a]. Currently, this transition is taking place, and the country's grid operator PLN has communicated in their 10-year plan that in the coming years more renewable power plants than fossil fuel plants are being commissioned.

Part of Indonesia's plan for the transition to net zero emissions is the implementation of a high share of renewable electricity technologies (RET). Starting with increasing the current share of 12.8% renewable generation to the target of 25% renewable generation in 2025. Recent assessments show that a big part of the country's power demand can be satisfied through solar, wind, hydro and biomass power that is available on the country's lands and seas [IESR, 2023, Langer et al., 2021]. However, the archipelago geography of the country resulted in disconnected power systems, the generated power on one island cannot be transported to other islands. As the most feasible locations for sun and wind power are located in the southeast part of the country and the highest demand is in the Java, Sumatra and Bali areas, the RET power supply is located in the same places as the country's demand. Studies indicate that this can cause challenges in dealing with the intermittency created by integrating renewable sources in the Indonesian power system [Burke et al., 2019].

1.2.1 Interconnection

Indonesia's energy sector is exploring the necessary steps to transition its power system to accommodate this new, renewable power supply. One of the identified steps by both Institut Teknologi Bandung (ITB) and the Institute for Essential Services Reform (IESR) is the need for interconnection between the power systems [IESR, 2023]. As Indonesia's power systems are distributed across its islands, interconnection of the main power systems would lead to inter-island interconnection. The idea of connection is being explored by the IESR, as they recently wrote a report on the deep decarbonization of Indonesia's energy system. The report highlights a substantial disparity between demand and generation on the main island's power systems and presents projections for necessary imported and exported energy Figure 1.1. Especially with the new capital being built in South Kalimantan, the demands of the Indonesian power systems will change in the coming decade. Through inter-island interconnection, the power from the distributed RET can be transported to high-demand locations [Breyer et al., 2021]. Despite these projections, the actual technical plan for the interconnections between islands is not mentioned. The report emphasizes the critical significance of inter-island interconnection [Breyer et al., 2021].

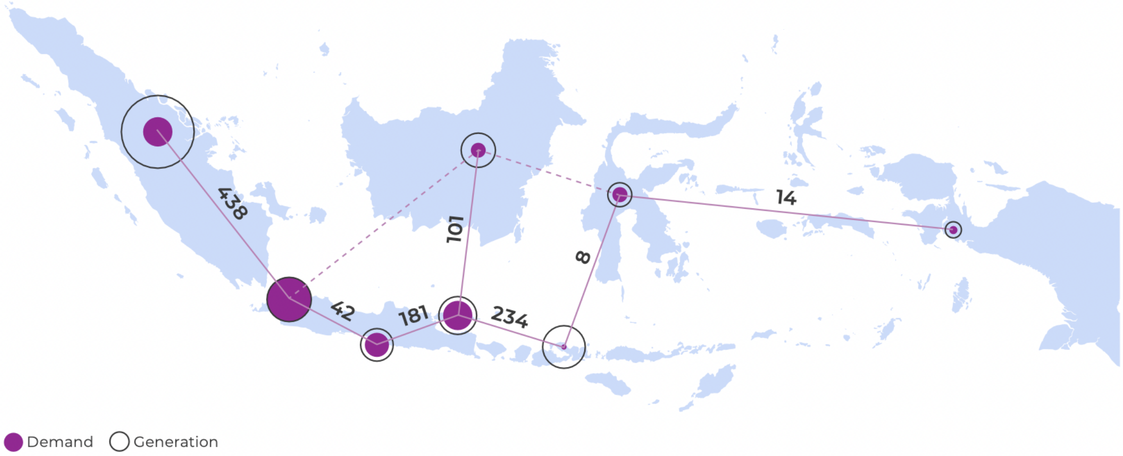


Figure 1.1: Illustration of projected annual imported and exported electricity between Indonesia's main islands in 2050 (in TWh) by IESR, [Breyer et al., 2021]

Interconnection has been demonstrated as an essential requirement for achieving the energy transition goals towards a truly sustainable power system in other regions of the world[UNFCCC, 2022]. For instance, the European energy transition has shown that interconnection contributes for the successful integration of RET, improves the security of the power system and lowers the electricity price [Child et al., 2019]. Studies that analyzed potential scenarios up until 2050 suggest that the European power system must become even more interconnected to facilitate. These same findings have also been reported in studies that compare interconnected and distributed power system scenarios for China and the United States [Aghahosseini et al., 2017, Wu et al., 2011, Atmo et al., 2022a]. Given the successful examples of interconnection for achieving a sustainable power system in other parts of the world, it is logical to explore the potential of interconnection for Indonesia as well.

However, the implementation of an inter-island interconnected system means that Indonesia's islands will be dependent on each other power system dynamics [IESR, 2023]. This can lead to an opposition to interconnection grounded in the risk of black-outs, imbalanced pricing and general lack of autonomy.

1.3 Problem statement

As described, Indonesia's power system is currently transitioning towards net-zero emissions by 2060, with a heavy reliance on renewable energy technologies (RET). This shift, however, presents new challenges, including unequal resource distribution between islands and RET intermittency. [Clark et al., 2017]. To address these challenges, research and reports propose the interconnection between Indonesian islands to establish a more reliable and secure power system [IESR, 2023]. However, the technical requirements, economic resources, and precise positioning of these interconnections have not yet been thoroughly examined in academia, as discussed in greater detail in section 2.2.4. Establishing such a system necessitates not only technical and economic considerations but also a transition to a new system for stakeholders and institutions. This thesis focuses on the optimization of the technical design of the inter-island interconnected system and what institutions play a role in the transition towards it.

1.4 Societal relevance

Interconnecting the islands of Indonesia through inter-island interconnections is a crucial element of the country's energy transition. Research towards this system is significant because it allows Indonesia to integrate more renewable energy technologies, which is in line with the seventh Sustainable Development Goal of 'Affordable and Clean Energy' [United Nations, b]. Additionally, inter-island interconnections will enhance energy security for Indonesian citizens and facilitate economic growth through national and inter-

national power trading.
The societal relevance of this research lies in its potential to transform Indonesia's power system into a net-zero system. By interconnecting the islands, access to renewable energy sources can be unlocked, benefiting many areas of the country that do not have equal potential for renewable resources. The ultimate goal of this research is to have a positive impact on Indonesia's energy transition by enabling the implementation of renewable energy technologies and promoting sustainable development.

1.5 Research objectives related to MSc program

The proposed research topic is an appropriate fit for the COSEM master program as it pertains to a physical system and also addresses the social and organizational dimensions of the system. Furthermore, the subject matter encompasses the complexities of implementing modern technologies, such as renewable energy sources. The research is relevant for various stakeholders including private entities such as grid-development companies, as well as public entities such as national vision makers and governmental decision-makers. The objective of this research is to make a trade-off for the technical design alternatives on inter-island interconnection in Indonesia and write a recommendation on the socio-cultural transition into the system. Based on these considerations, it can be inferred that the proposed research topic aligns well with the focus of the COSEM program.

1.6 Thesis Outline

This thesis consists of two main parts: techno-economic optimization and institutional analysis. Foremost, section 2, starts with the description of the knowledge gap and research questions. Then, the first part begins with a brief chapter that explains the historical background and current state of inter-island interconnections (section 3). Following this, a chapter outlines the methodology used for the optimization (section 4), and then there's a review of existing literature concerning the crucial criteria for interconnections (section 5). Finally, the actual results of the optimization and their analysis are presented (section 6).

Moving on to the second part, the institutional analysis starts with an explanation of the methodology employed (section 7), which is then used to derive institutional findings on the current institutional setting and its barrier to the development of inter-island interconnections (section 8). These findings are subsequently examined to create recommendations for policymaking (subsection 8.6). To conclude, the thesis wraps up with a discussion (section 9) of the results obtained and presents a final conclusion (section 10).

This introduction chapter provides an introduction to the subject of this study; inter-island power interconnections in Indonesia. The chapter presents the motive for the selection of this topic, the problem statement and why the topic is related to the master program 'Complex Systems Engineering and Management'. Lastly, the chapter provides an outline of this document.

2 Literature review, knowledge gaps, and research questions

To understand the current state-of-the-art of academic research on interconnection in Indonesia's power system, relevant literature is reviewed. In section 2.1, the core concepts that are the foundation of understanding the literature are explained. Then, section 2.2 will give an overview of the existing academic literature concerning inter-island interconnections in Indonesia. This will be followed by the determination of knowledge gaps in section 2.2.4 and research question 2.2.5.

2.1 Definition of core concepts

2.1.1 Indonesia Power System

Indonesia is one of the world's biggest archipelagos nations, made out of over 17000 islands of which about 6000 are inhabited [Kunaifi et al., 2020a]. The islands all have their own power system including power generation, transmission and demand. Around 70% of Indonesia's power generation is consumed in Java and Bali, 12% in Sumatra and the rest is divided between the other islands. Java and Bali are connected through an interconnection system [Handayani et al., 2017]. The interconnection between Java and Bali is currently the only interconnection between Indonesia's islands. The transmission and distribution network is to this point completely developed and maintained by the grid operator Perusahaan Listrik Negara (PLN) [Kunaifi et al., 2020b]. As described in section 1.2, Indonesia's power system is in transition, guided by targets concerning the percentage of power generated by RET and the amount of GHGE. However, analysis shows that the current power system will not be able to accommodate these targets while maintaining its balance. Therefore, the power system of Indonesia will need to change in order to meet its countries goals.

2.1.2 Renewable energy technology potentials

As Indonesia has objectives of reaching net-zero in 2060 [IESR, 2023], the country's renewable energy technology (RET) potentials are being explored. These potentials include, among others, geothermal, hydro, solar, wind and OTEC technologies. The most basic RET potentials describe the gap in an area's power generation using RET between the present and the potential future considering the availability of sources like wind, sun, geothermal and more (Physical/theoretical potential) [Blok and Nieuwlaar,]. However, the RET potentials do not only depend on the availability of sources but also on barriers and drivers of the market in which the RET will be used (Market potential) or if the RET is economically feasible in that specific location (Economic potential). Within this research, the economic potential of RET is used in order to provide a realistic view on the potential or RET implementation in the future. This economic RET potential is defined as; the amount of RE output projected when all – social and private – costs and benefits related to that output are included [Verbruggen et al., 2010]. Research suggests that Indonesia has economic RET potential on its lands and seas. The potential is even enough to satisfy the demand of a 100% renewable energy system [Langer et al., 2021].

2.1.3 Inter-Island Interconnection

Inter-Island Interconnections are the term used to describe the connection of disconnected power grids between islands. After the interconnection, the connected power grids operate at the same frequency. This provides an infrastructure for power to flow from one system to another. Interconnecting power systems create various benefits whereas the economic and security aspects as the most important ones [Wu et al., 2011]. The concept of interconnection sounds realistic however, it also brings its challenges. First of all, since power grids can be far apart, long transmission cables have to be used for interconnection. Often these cables are either High Voltage AC (HVAC) or High Voltage DC (HVDC) cables that can be used on land or through seas [Nguyen et al., 2010]. The installation of interconnection cables is a costly and complex project, and the synchronization of power system frequency is necessary for interconnecting power systems. Additionally, interconnecting power systems means that they will become interdependent on each other. Thus, it is crucial to use comprehensive power system analysis when designing an interconnected system [Venkatasubramanian and Tomsovic, 2004].

Moreover, interconnecting islands through submarine interconnections poses additional challenges due to the geographical features of the islands. The location and layout of the cables should be optimized based on factors such as the distance between the islands, the water depth, and other geographical features. [Ardelean and Minnebo, 2023]. For Indonesia specifically, various inter-island cable configurations are possible and ready to be explored.

2.1.4 The institutional side of electricity system transformation

The power system in Indonesia is a complex network that involves multiple actors such as transmission operators, policymakers, system designers, and consumers, as well as various institutions and collaborations. As the power system undergoes a transition towards an inter-island interconnected system, this complex system will also undergo a transition. To understand and explore how to stimulate this transition, institutional analysis will be used, for which various approaches are available. Including various frameworks to analyze the dynamics of the system, such as the multi-level perspective (MLP) or the Institutional analysis and development framework (IAD) [Ostrom, 2005]. The MLP framework focuses on the interplay between niches, regimes, and landscapes. Researchers Verbong and Geels have employed the MLP framework to examine the transition to an interconnected European Supergrid. [Verbong and Geels, 2010]. Another framework that can be used to analyze the institutional side of the transformation of the electricity system is the four-levels framework of Williamson. It is based on the idea that institutions exist at different levels of a socio-technical system, and that each level has its own set of dynamics and purpose [Williamson, 1998].

2.2 Literature search

2.2.1 Method

With these core concepts in mind, the current literature can be better understood and analyzed. The selection of the literature that is used for a literature review is done through the use of the program Scopus. On this website, a search query is created using the core concepts and keywords of the topic. This query looks like this:

"Power" AND ”Interconnection” AND ”Indonesia”

Moreover, to ensure that the articles in this review are relevant and up to date on this fast-developing topic, only articles of the past 5 years are included. The number of articles that are found after these requirements can be found in the following Table 1.

The summary of this analysis can be found in the appendix Table A.1.

2.2.2 Result of literature review

The studied research shows that power grid development and interconnection is currently an active topic. Various models and simulations are analyzed throughout Indonesia which include interconnected systems [Tumiran et al., 2022a, Atmo et al., 2022b, Tumiran et al., 2022b, Sutardi et al., 2019, Ajami et al., 2019]. Research suggests that beyond interconnecting within Indonesia, there could be significant benefits to interconnecting with other countries. For instance, Wang's study indicates that connecting Australia's and Indonesia's power systems could have positive impacts for both nations. [Wang et al., 2018]. Another example is that according to Ardyono, interconnecting the countries located on Kalimantan would unlock an optimal dispatch strategy for the power system.[Ardyono et al., 2019]. Furthermore, interconnection has been identified as a potential solution for addressing the intermittency of renewable energy technologies, as demonstrated in a research study on two wind power parks.[Arief et al., 2020, Ajami et al., 2019].

However, the existing academic literature on inter-island interconnection in Indonesia is limited, with few studies analyzing its necessity or optimal configuration. Burke et al. have suggested that inter-island interconnection could improve Indonesia's power system [Burke et al., 2019], but further information on these structures is mainly available through official reports from research institutions like IESR [IESR, 2023] and collaborations such as those led by Breyer [Breyer et al., 2021]. As power systems are complex and interconnections cause even more complexities, comprehensive modelling is necessary to create a sufficient design for the system. As described by Ardelean and Minnebo, the optimal configuration of inter-island interconnections are influenced by, among more, distance between substations, water depth, spatial features, population number and density [Ardelean and Minnebo, 2023]. These factors are not yet considered by the analysed academic literature.

Additionally, it is important to mention that the literature reviewed through the query does not address the institutional dimension of power system interconnection. However, studies outside research focused on Indonesia indicate that the restructuring of power systems has an impact on the interactions among power consumers [Clark et al., 2017].

2.2.3 Additional grey literature

Due to the recent timing of the suggestion for inter-island interconnection in Indonesia, additional 'grey' literature is being published on the topic. This literature is not published in a peer-reviewed academic medium but through other (commercial) organizations. For instance, the International Energy Agency states in their report about the energy transition in Indonesia that interconnection between the islands will allow the implementation of more RET [International Energy Agency, 2020b]. Moreover, professor Pekik Argo Dahono from the ITB university in Indonesia pusblished a presentation on the 'Nusantara Super grid' which is a concept including the inter-island interconnection of the main island [Dahono, 2021]. During the presentation, the professor discussed the potential advantages and obstacles of an inter-island interconnected power system without delving into its actual design. Similarly, D-insights, an Indonesian newspaper, reported that inter-island interconnections were being advocated for by various government officials during an interview focused on Indonesia's energy transition [D-Insights, 2021]. Based on these sources, there is support for the concept of an inter-island interconnected grid from multiple stakeholders involved in Indonesia's energy transition.

2.2.4 Knowledge gap

Based on this literature analysis, it is evident that the current state-of-the-art regarding power system interconnection is quite dense. The significance of interconnection in dealing with intermittent sources is frequently emphasized. However, academic literature on specifically inter-island interconnection in Indonesia is lacking, which is crucial for the implementation of Renewable Energy Technologies (RET) in Indonesia. The analysed studies have confirmed the necessity of power grid development and demand-supply equilibrium as more RETs are adopted. Additional grey literature suggests that inter-island interconnections are a promising concept that requires further exploration. However, the literature does not provide any information on exactly which inter-island interconnections are feasible to develop and what technological features should be considered in their development. Moreover, the literature does not write about the institutional changes that play a role in the transition to power system interconnection in Indonesia. Therefore the identified knowledge gap is the determination of this configuration and how the transition to an inter-island interconnected system influences the institutional dimension.

2.2.5 Research question

The purpose of this thesis is to contribute to the identified knowledge gap by exploring how to optimally implement and transition to an inter-island interconnected system in Indonesia. Therefore, the main research question to be explored is:

> *"Which inter-island interconnection routes are feasible to accommodate renewable energy technology integration in Indonesia and what are the needed institutional adjustments for fostering such an interconnected system?"*

2.2.6 Sub-questions

To organize and structure the research, the primary research question is divided into four smaller sub-questions. The first sub-question seeks to establish the requirements that will serve as input for the power system model. The second sub-question concerns the development and optimization of the power system model itself. Once optimal model alternatives are generated, the third sub-question addresses the transition towards the new system and the roles of relevant actors and institutions. Finally, the fourth sub-question explores the drivers and barriers associated with the transition to the new power system, concluding the research.

1. *What technical and economic requirements are critical for the feasibility of inter-island power interconnectors?*
2. *What are feasible and necessary interconnection routes to interconnect neighbouring islands to each other in the power system in Indonesia?*
3. *What are the institutional barriers to the development of an inter-island interconnected power system in Indonesia?*
4. *What are the needed institutional adjustments to promote an inter-island interconnected power system in Indonesia?*

2.3 Research Approach

The research approach of this study can be divided into two parts, this section will describe the reasoning behind these approaches. Then, the following subsections will further describe the selection progress for the modelling tool and institutional framework which shape and guide the methodology of the study.

As the use of energy planning modelling is often used as guidance and material for discussion about how future energy systems should be developed, the first part of this research will be conducted through a modelling approach [Cao et al., 2016]. Using a model to answer the first part of the question allows a risk-free way to simulate the new electricity infrastructure system for different scenarios. However, the results created by the model depend on the data accuracy and assumptions that are taken as the input of the model, commonly known as the 'garbage in, garbage out'-principle. [Aughenbaugh and Paredis, 2004]. Thus, it's crucial to reflect on data validity to interpret results properly.

As electricity infrastructures are complex socio-technical systems [Kunneke et al., 2021b], a more comprehensive approach is chosen to draw a better picture of reality. Therefore, the second part of this study entails a qualitative institutional analysis, focusing on the potential institutional challenges that come with the planning of electricity infrastructure. Through this addition, the results of the model are framed into the existing institutional context that is not considered in the model itself [Scholten and Künneke, 2016]. s

2.3.1 Modelling tool

The objective of this study is to explore the need and possibilities of inter-island interconnection in Indonesia to provide an electricity infrastructure that can accommodate the renewable energy technologies necessary to reach the 2060 net-zero target and assist decision-makers in doing so. The technical components of electricity infrastructure can be summarized into generation, transmission, distribution and consumption [Fodstad et al., 2022]. These components are the building blocks of, energy planning models, therefore, these types of models are chosen to conduct this study. These types of models use demand and generation data to model scenarios under a given set of constraints. In this decade, various energy planning models have been developed and analysed. As described by Pfenninger et al., in this century energy system models are a necessity to deal with the ongoing energy transition and the challenges that come with it [Pfenninger et al., 2014]. Important challenges are rising demand due to electrification and intermittency of supply due to the increase of electricity generated by renewable sources [Pfenninger et al., 2014]. The use of scenarios provides a way to argue and explore the possibilities of a decarbonized energy system and is, therefore, an interesting tool in energy system modelling.

This rise in energy models also caused a range of different models with different characteristics. To select the appropriate model for this study, these characteristics are examined, and the following section will describe the trade-offs. The first characteristic is the division of energy system models into top-down and bottom-up models. Whereas the results of a bottom-up model are built up from all its (technical) components, top-down models start with the result and then bring in more detail along the way[Swan and Ugursal,]. As this is an explorative study, the bottom-up approach will better suit the objective of the study.

The second characteristic is the division of simulation models and optimization models. Whereas energy system models were historically mostly created to optimize systems, a simulation approach is focused on predicting the most likely evolution of the system [Pfenninger et al., 2014]. This study is focused on exploring different scenarios in which inter-island interconnections are used to accommodate a new generation mix. Therefore, by using an optimization model, these scenarios can be solved.
Next to these two characteristics, there are also two challenges that are important to consider for selecting the model. The first relevant challenge of energy system models is the importance of temporal resolution. Since the current developments in energy systems are dynamic and variant, it is important that the energy model has a high temporal resolution, containing various days and even variability within days[Pfenninger et al., 2014]. A current trend is the use of one-hour step temporal resolution and this is therefore a needed characteristic of the used model. Another challenge to consider is the complexity of scale, there is a trade-off between details/resolution and scale of energy system models. Currently, energy system models are often either focused on a large (geographical) scale for instance a whole continent, but because of the limitations of space and computational power, they do not include all the complex details of the reality. Smaller scale models often do include more detail and are therefore closer to reality. Since this study concentrates on the entire country of Indonesia, it should be kept in mind that the energy system model could be lacking in representing reality due to its scale[Pfenninger et al., 2014].

Considering these trade-offs and the model objective, numerous energy system models are identified as usable (PyPSA, Calliope, PLEXOS, PandaPower, and many more [Fodstad et al., 2022]). However, researchers from TU Delft have already modelled a large part of the power systems in Indonesia [Langer et al., 2021] in Calliope. Therefore, this model can be used as a foundation to explore the inter-island-interconnections. Therefore, this model is chosen as the energy system model for this study. The steps in using this model are first the conceptualization of the system, the pre-processing of input data, the determination of decision variables and constraints, the optimization of scenarios and finally the analysis of the results [Pfenninger and Pickering, 2018].

Next to the modelling of scenarios, this study also investigates the feasibility of the generated electricity system in the energy model. As mentioned, the challenge of large-scale energy models is the lack of realistic representation. As determined, the geographical features of Indonesia are often mentioned as a barrier to the development of inter-island interconnections. Therefore, this study explores the actual impact of these geographical challenges through a geographic information system (GIS) analysis. This model approach is based on studies on the spatial evaluation of interconnection cables in other regions [Makrakis et al., 2023, Itiki et al., 2020a, Wang et al., 2019]. The steps for doing this analysis are to first gather the geographical data, add criteria weights to the geographical characteristics, and analyze the influence of the weighted criteria on the development of inter-island interconnections.

2.3.2 Institutional Framework

The institutional framework that is selected for the institutional analysis is the Four Level of Williamson framework. The in-depth reasoning for the selection of this framework can be found in subsection 7.4. The application of the framework is done through qualitative desk research. This includes the use of literature found in academic sources, industry reports and official regulations. This decision is made because of the wide availability of literature on the topic and the limited timeline of this study. The four-level framework of Williamson is used to analyse the current institutional setting and three aspects within the second and third levels of the framework. Through analysis barriers will be identified. Finally, recommendations will be provided on how to lower these barriers and open the path to the development of inter-island interconnections.

This second chapter describes the initial literature study that results in the determination of the knowledge gap that this study aims to address. Following the knowledge gap, the research questions are formulated. The chapter concludes with an overview of the research approach, encompassing both techno-economic optimization and institutional analysis, along with a discussion of the associated trade-offs.

3 Theoretical background on submarine transmission cables

This chapter will briefly describe the theory of submarine power transmission technology to provide the necessary theoretical background to interpret this study.

3.1 Long distance transmission infrastructure

Indonesia is currently undergoing a crucial energy system transition to achieve its ambitious target of net zero emissions by 2060 [Government of Indonesia, 2014b]. Achieving this objective necessitates the incorporation of emerging renewable energy technologies. Unlike traditional fossil fuels like coal, oil, and gas that can be easily transported to fulfil energy needs, many renewable sources face geographical limitations [Clark et al., 2017]. Hence, creating links between these sites of renewable energy generation and regions with substantial electricity requirements becomes a necessity. These links are enabled by transmission cables, which function as the electrical transportation network within the electricity grid [Blok and Nieuwlaar,].

However, the existing electricity grid in Indonesia is ill-suited to transmit electricity from renewable sources to regions with high demand [Maulidia et al., 2019, IESR, 2023]. Expanding the infrastructure emerges as a viable approach to enhance the electricity grid's capacity. Given Indonesia's archipelago geography, connecting regions with abundant renewable energy potential to areas with high demand necessitates the establishment of interconnections between the islands using submarine cables [Ordonez et al., 2020]. As described in subsubsection 2.1.3, when two power systems are linked, it is commonly referred to as "interconnection," and specifically, when the connection occurs between two islands, it is known as "inter-island interconnection" [Itiki et al., 2020a].

3.1.1 Overview of the role of transmission in electricity infrastructure

Electricity infrastructure is the entire system of the generation, transmission, and distribution of electricity [Blok and Nieuwlaar,]. It includes power plants, substations, transformers, transmission lines, distribution networks, and other components that form the power grid. The purpose of this infrastructure is to ensure a reliable and stable supply of electricity to meet the needs of consumers [Clark et al., 2017].

Long-distance transmission plays a crucial role in the electricity infrastructure because it allows for the efficient transfer of electricity from generation to demand, such as in densely populated cities or industrial hubs [Venkatasubramanian and Tomsovic, 2004]. Transmitting electricity over long distances optimizes the utilization of diverse energy resources and helps meet the demand for electricity even in regions where local generation capacity may be limited[Venkatasubramanian and Tomsovic, 2004]. The transmission of electricity over long distances is typically achieved through high-voltage transmission lines. These lines are designed to minimize energy losses during transmission and ensure that electricity can be transported safely and reliably over thousands of kilometres. Transformers and substations are utilized along the transmission route to regulate voltage levels and maintain the quality of the electricity being transmitted.

High voltages enable efficient transmission of large amounts of electric power across long distances. Higher voltages result in lower efficiency losses. The losses of power are influenced by factors such as the conductor type, line length, cross-section, and current type (AC or DC). The technologies that are currently used for high voltage power transmission are 'High Voltage Alternating Current' (HVAC) and 'High Voltage Direct Current (HVDC)' Figure 3.1.

In high-voltage direct current (HVDC) transmission, electric current mainly flows through the wire, while high-voltage alternating current (HVAC) transmission experiences the skin effect, concentrating current near the surface. This effect reduces effective cross-section, raising resistance and power losses [Ardelean and Forename, 2015]. Moreover, when electricity is transmitted over long distances using traditional AC (alternating current) cables, there can be significant energy loss. However, by using HVDC (high-voltage direct current) cables, these losses can be minimized. HVDC also provides better control over power flow, enabling efficient integration of renewable energy sources and interconnection of different power grids. This, among other aspects, is the reason why HVDC is cheaper than HVAC when overhead lines go over 1000 km and submarine cables over only 50 km [Schavemaker and Van der Sluis, 2008], as displayed in Figure 3.2.

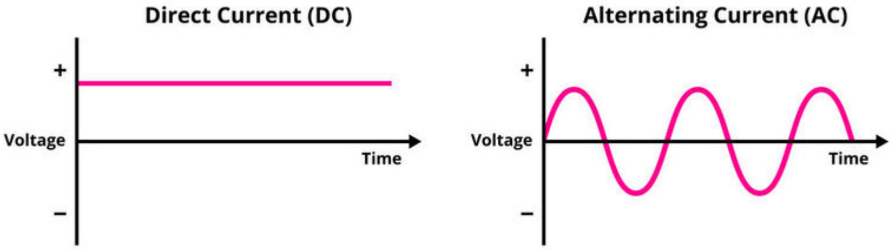


Figure 3.1: Difference DC and AC current

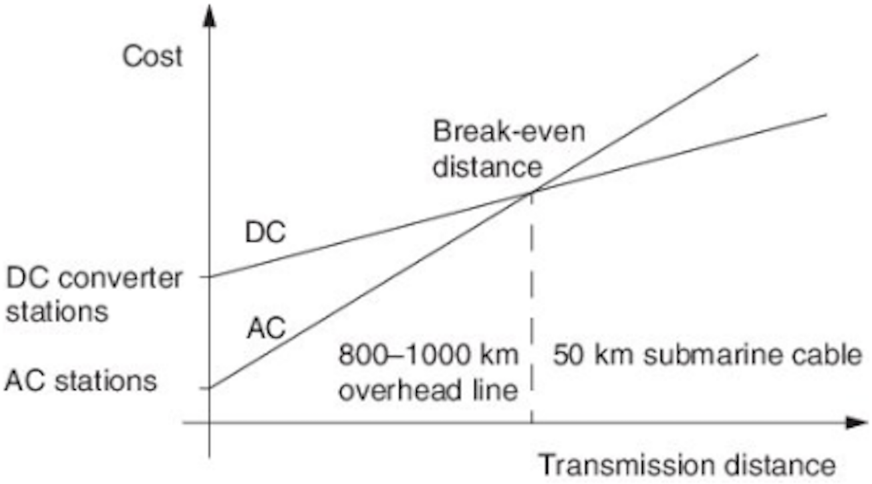


Figure 3.2: Break-even point between HVDC and HVAC current lines and cables [Schavemaker and Van der Sluis, 2008]

3.2 Rise of submarine HVDC cables

SSince its establishment in 1954, the Gotland HVDC link has held a significant role as the first subsea HVDC cable. Stretching 50 km, it successfully connected Gotland island to mainland Sweden, working at 100 kV with a power capacity of 20 MW [Ardelean and Forename, 2015]. Over time, subsea HVDC cables have developed into a well-established technology, now spanning approximately 10,000 km globally, mainly in Europe. These cables often have power ratings exceeding 100 megawatts (MW), typically falling within the range of 500 to 12000 MW [Hitachi Energy, 2023a].

In recent times, notable progress has led to captivating breakthroughs in this domain. These strides have made it possible to create subsea power cables equipped to manage significantly higher voltages, extending up to 600 kV. Moreover, these enhanced cables provide notably elevated power capacity, with the potential to convey as much as 12,000 MW of electricity. [Wang et al., 2018].

To give an idea of lengths, capacity location and water depth, the following Table 3.1 shows a sample of existing or planned submarine power cables, adapted from [Gordonnat and Hunt, 2020]. As depicted in the table, the cable lengths vary from 420 to 1000 kilometres, accompanied by water depths spanning from 50 meters to 3000 meters.

Table 3.1: Overview sample set of existing or planned submarine HVDC interconnections, adapted from [Gordonnat and Hunt, 2020]

Link name	Length (km)	Capacity (MW)	Location	Voltage (kV)	Commissioned	Max. water depth (m)	Cost (million €)
EuroAsia	1000	2000	Israel, Cyprus, Greece	500	Planned 2026	3000	760
Neuconnect	720	1400	UK Germany	400	Planned 2023	40	2800
North Sea link	700	1400	UK Norway	450	Planned 2022	600	2000
NorthConnect	650	1400	UK Norway	525	Planned 2024	860	1700
Viking link	630	1400	UK Denmark	525	Planned 2023	50	2100
NorNed	580	700	Netherlands Norway	450	2008	400	600
Celtic interconnector	500	700	Ireland France	500	Planned 2026	100	1600
Western HVDC link	420	2200	UK	600	2018	120	1200
SAPEI	420	1000	Italy	500	2010	1600	730

Chapter three explores the theoretical background of submarine transmission cables, diving into the history, technology and best practices of existing HVDC submarine systems. The information in this chapter is necessary for the reader to understand the following chapters, it can be seen as a theoretical base for reading this study.

4 Power System Optimization: Methodology

This chapter describes the steps taken in the power system optimization of the (simplified) power system of Indonesia. As described in subsection 2.3, the power system optimization is divided into two parts. First, the optimization of the power system using the energy system modelling software Calliope. The second part exists of a feasibility study using a GIS analysis approach where a shortest path analysis is combined with a multi-criteria decision method. Together these two parts aim to explore the possibilities and barriers of inter-island interconnections in Indonesia. The first section of this chapter describes the stepwise methodology used in the Calliope optimization. These steps are based on the steps from the Calliope documentation and are in line with general model optimization steps. These steps are (1) Create a model from scratch or by adjusting an existing model (Building the model), (2) Run the model (Running the model), (3) analyse and visualise model results (Analysing the model) [Pfenninger and Pickering, 2018]. These steps will be further discussed in the following sections. Moreover, the GIS analysis will be described. This analysis consists of the following steps; (1) gather the geographical data, (2) add criteria weights to the geographical characteristics, and, (3) analyze the influence of the weighted criteria on the development of inter-island interconnections. These steps will also be described in the following sections.

4.1 Calliope - Building the model

To use Calliope, the build of the model is the first step. In the case of this study, the model will be built on an existing model created by PhD researcher JKA Langer. This model is available open-source through this GitHub link, using version [v0.6.10] [Langer, 2023]. Although all the information about how the model is built can be found on the GitHub page, this section will give an overview of the input variables and constraints. The data that is used as input for the model can be divided into five types, locations, supply technologies, storage technologies, demand technologies and transmission technologies. The following subsections will further describe the data that is used within these types.

4.1.1 Scope and locations

The scope for this energy system optimization using Calliope is, as described, Indonesia. However, the country is simplified in the model to reduce the computational power since not all details are necessary to work towards the objective of this model. The objective of the Calliope model is to analyse how Indonesia can meet its decarbonization targets in 2060. However, in the Calliope model made by JKA Langer (2023), the projected demand data sets are up to 2050. Therefore, in this study, the demand projection for 2050 will be used, as this is the closest to 2060 as possible. This is approached by using the 38 provinces of Indonesia as reference locations. So all the demand, supply and storage of one province are aggregated and used as one reference point in the model. These reference points are the 'locations' in the model. Each location is also the reference point for transmission technologies, so a transmission cable can only be used between two locations. The following Figure 4.1 demonstrates the organisation of the location reference point on the map of Indonesia with green points on the coordinates of the locations. As can be seen in the figure, the model contains the original Indonesian names for the locations, as implemented by researcher JKA Langer. This study will follow his lead and keep this naming. The Indonesian words: Utara, Timur, Selatan, Barat and Tengah translate to North, East, South, West and Middle in that specific order.

Figure 4.1: Provinces of Indonesia with green points as an indication of the location reference point [Langer, 2023]

4.1.2 Supply Technologies

As the objective of this study is to explore the necessity for inter-island interconnections under the net-zero target in Indonesia, only renewable energy supply technologies are included. In the Calliope Indonesia model by researcher JKA Langer [Langer, 2023], the included renewable supply technologies are the following: Hydropower (large and small), geothermal power, solar power, wind power (onshore and offshore), biomass power, nuclear power and OTEC power. The input data for the supply technologies is predicted generation data for 2050. The original model contained two different types for this data set, either the minimal generation of the technologies or the average (mean) predicted generation of the technologies. For this study, the average (mean) generation data is used for each supply technology since it tries to capture the most likely scenario and not the worst-case scenario. The generation data for each supply technology is a prediction for 2050 and is based on various studies performed by researcher JKA Langer, TU Delft master thesis students and other academic sources [Langer, 2023].

4.1.3 Storage Technologies

The Calliope Indonesia model has included predictions for the capacity of storage technologies in Indonesia in 2050. As described, storage technologies are a promising method to make sure renewable can serve the demand of Indonesia at all times through storing and releasing electricity at the right moments. The two storage technologies that are included in the model are batteries and pumped hydro energy. The capacities for these storage technologies are based on predictions made by researcher JKA Langer [Langer, 2023] and other academic sources.

4.1.4 Demand Technologies

The Calliope Indonesia model contains a data set as input data for the demand. This data is, as mentioned, aggregated per province. There are three different data sets available in the model, including demand predictions for multiple years (2030, 2040, 2050), and different demand fluctuation scenarios (low fluctuation, high fluctuation, extreme fluctuation). This study focuses on the year 2050, and will therefore only use the demand profile predictions data set for 2050. Moreover, only the low and high fluctuation scenarios are included due to the limited timeline of this study. The following section will summarize the method of how the demand profile prediction is done, adapted from [Langer, 2023].

As described in the introduction, the electricity demand in Indonesia is not equally distributed over the country of Indonesia. The demand is mainly centered in the provinces of Sumatra and Java, this can be seen in Figure 4.2, where the average demand of each province is indicated with the size of green the circle.

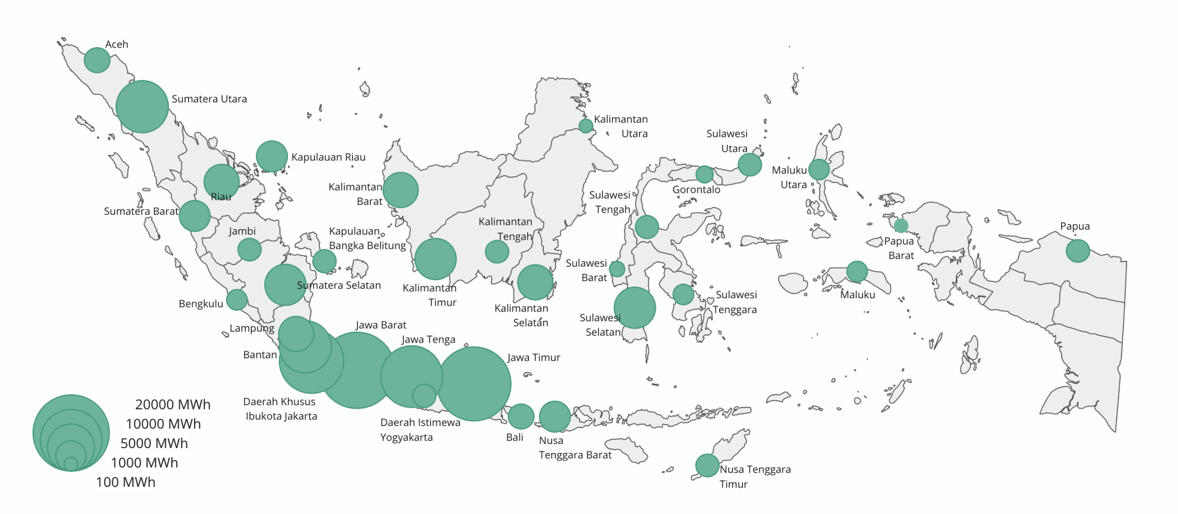


Figure 4.2: Provinces of Indonesia with green points as an indication of the average predicted demand for the year 2050 as the size of the circle

The difference between the demand fluctuation scenarios can best be seen in the plot of the aggregated demand for the entire country in a single province, normalized for the highest demand. The following Figure 4.3, shows the difference between the predicted demand in the low fluctuation and high fluctuating scenario in 2050.

4.1.5 Transmission Technologies

Within the Calliope Indonesia model, all the provinces that are on the same island, are connected through an AC power transmission network. Figure 4.4 illustrates the AC connections as blue lines between the reference point for the province locations (green points).

The original purpose of building the Calliope Indonesia model was to explore how Indonesia can achieve the net zero target by only running on renewable supply technologies [Langer, 2023]. The results of this initial model and study show that without inter-island interconnection, the predicted demand for each province in Indonesia in 2050, cannot be met with the supply and storage technology potentials. Therefore,

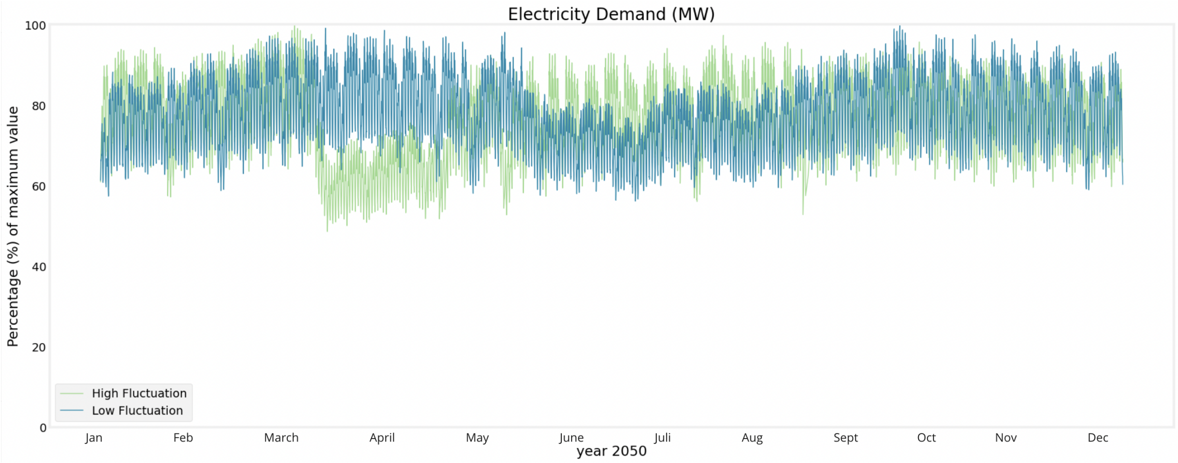


Figure 4.3: Predicted demand difference for the low and high fluctuating scenario in 2050 for all provinces in Indonesia [Langer, 2023]

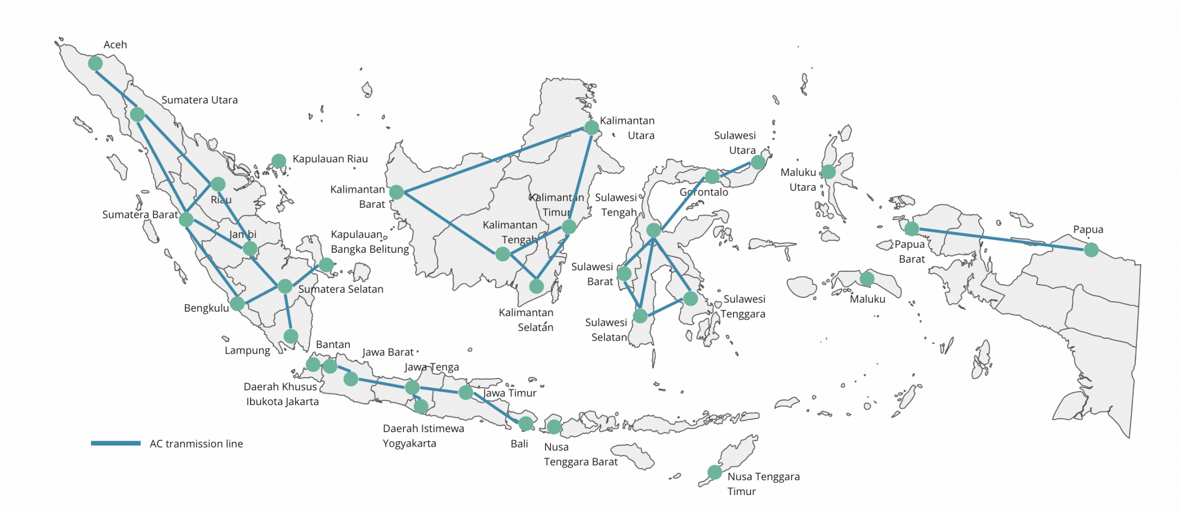


Figure 4.4: Provinces and on-land AC transmission network [Langer, 2023]

the model contains the option of HVDC submarine transmission interconnection technology. The initial study found that through the use of these technologies, the demand can be met by the predicted supply technologies. However, in the initial study by researcher JKA Langer, the model was limited by the use of only a few transmission technologies between the islands. These technologies are based on a presentation that was demonstrated when Pemodelan Tim NZE KESDM, presented at the Institute of Technology, Bandung, Indonesia, on 18th Oct 2022. The most crucial change that this thesis study contributes to the model is the further exploration of which HVDC cables are necessary and feasible to connect the islands.

The method for this exploration is an iterative approach in which the modelling will start with programming all possible inter-island interconnection between neighbouring islands. This means that all possible interconnections are programmed into the model but are given a minimal capacity factor of 0, therefore, the model can make the decision to not use the line at all during the optimization. As will be described in subsubsection 4.2.1, Calliope will make this optimization decision based on cost optimization. Through programming all possible interconnections but using a minimal capacity factor of 0, the optimization of the model will have the opportunity to choose which interconnections are most favourable to use in that scenario.

As determined from literature in section 3 the inter-island interconnections will use a HVDC technology. Within Calliope, technological criteria are used to determine the specifics of the HVDC interconnections.

The technical specifications are the same for each interconnection, only the length of the cables are different for each HVDC interconnector, the used distances can be found in the appendix. The specifications that are used for the HVDC transmission technology can be found in the following Table 4.1

Table 4.1: Specifications used for the HVDC transmission technology in the Calliope model

Specification	Value	Source
Energy efficiency per distance	0.9999565 % per km	[Patrik J. Kiger, 2012]
Cable lifetime	40 years	[Lombardi et al., 2020])
Interest rate	0.1	[Lombardi et al., 2020]
Capital Expenses	870000 US$/MW	[Lombardi et al., 2020]
Operational Expenses	2.552 US$/MWh	[Lombardi et al., 2020]

4.2 Calliope - Running the model

The Calliope model will be executed to optimize the power system based on costs while aiming for a balance between energy supply and energy demand under scenarios. These scenarios are built to test the configuration under different circumstances. Since the supply and demand data are projections, it is important to evaluate different options since projections are not set in stone. Scenarios are a method to somewhat decrease the uncertainty that comes with energy modelling and predictions [Fodstad et al., 2022]. Therefore, the model will be run under two different scenarios, in these scenarios, the availability of HVDC interconnection between neighbouring islands will vary per run. The following section will first describe the mathematical optimization method that Calliope uses to optimize the model, thereafter, the scenarios that are used in the model optimizations and finally the iterative method of the optimization.

4.2.1 Calliope optimization method

The Indonesia Calliope model is built on the is an open-source Calliope framework [Pfenninger and Pickering, 2018].

The logic of the optimization is visualized in Figure 4.5. As can be seen, the logic contains the technologies, demand and locations as input, has various constraints and decision variables and gives various outputs. In the figure, the red-lined blocks are the variables that are changed in the scenarios whereas the yellow-lined block is the most important output that this study looks at, the capacities of the transmission network.

The actual mathematical functions for the operation of the Calliope optimization can be found on the Calliope website [Pfenninger and Pickering, 2018]. In this study, these functions will not be specifically repeated. To give a general idea of what the functions consist of, the following Equation 1 demonstrated the highest objective function. This equation shows the minimization of the total system costs (*z*), which is the sum of the costs (*costs*) of the technologies (*tech*) used in each location (*loc*) multiplied with the weight (*weight*) of each cost class. Calliope provides the option to allow unmet demand, so the system is not in balance. For this study, this option is not used because the objective is to have a balanced system.

$$z = \sum_{loc::tech_{cost},k} (cost(loc :: tech, cost = cost_k) \times weight_k) \tag{1}$$

4.2.2 Scenarios

The scenarios are created with the objective of removing a slight part of the insecurity of the prediction. All the scenarios contain input data for the year 2050. This year is chosen because it is the closest to the target year 2060 of being net-zero while being in the data set provided in the Calliope Indonesia model. The resolution for the input and the output of the model is hourly. The optimization considers the entire year 2050, and the costs are therefore optimized for the annual system costs.

The difference between the scenarios is created by the change in the predicted demand profile. For the demand profile, either the low fluctuation or the high fluctuation prediction for 2050 is used. The scenarios are the following:

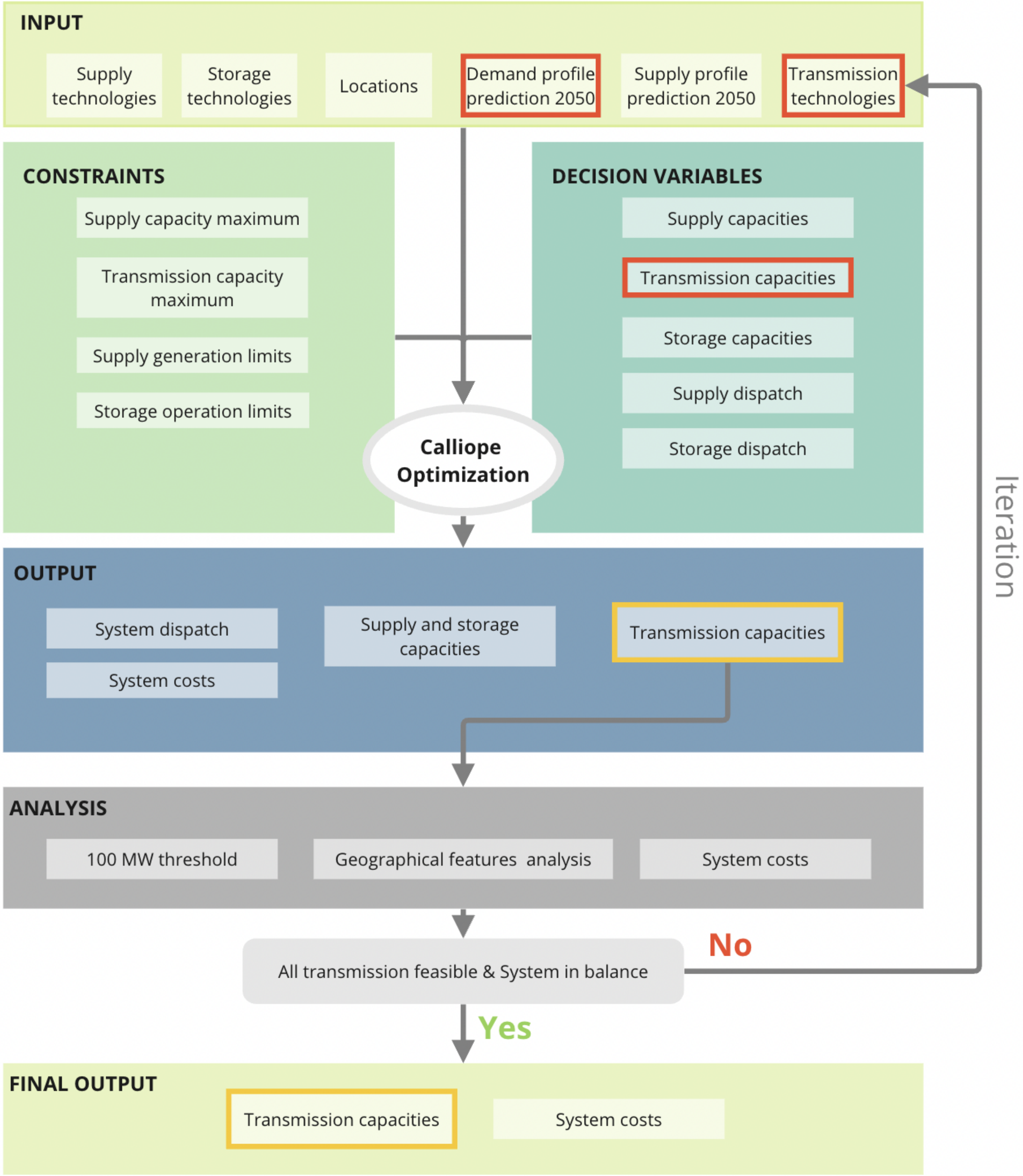


Figure 4.5: Logic of the Calliope optimization showing input, output, decision variables and constraints, the red-lined blocks are different for the scenarios and the yellow-lined block is the most important output

1. The first scenario contains all possible transmission interconnection technologies between all the neighbouring islands, under the low fluctuating demand prediction for 2050.
2. The second scenario contains all possible transmission interconnection technologies between all the neighbouring islands, under the high fluctuating demand prediction for 2050.

4.2.3 Iterative process

The first optimization of the Calliope optimization will result in a set of HVDC interconnections that the model selected to be necessary. However, as determined in section 3, HVDC interconnections are complex to construct and expensive. Moreover, various geographical features influence the feasibility of HVDC interconnections. Therefore, the results of each Calliope optimization will be analyzed on their feasibility. The measures used for this are the maximum capacity that the cable requires, and the geographical features that will be further described in subsection 4.4 and determined in section 5. As found in section 3, HVDC interconnections are usually used from 100 MW onwards. However, after testing the Calliope model, it appeared that it is not possible to include this logic in the model. Therefore, the analysis will determine if the interconnector is below or above this 100 MW threshold. If the interconnector is used for a lower power capacity than this threshold, it will be removed from the next iteration. After each run, the analyses will determine which cables are feasible or which are not. Then, the non-feasible interconnections will be removed from the model. Whereas after this, the model will be run again, until all cables are feasible.

4.3 Calliope - Analyzing and validating the model

The results obtained from running the Calliope model and its iterations provide insights into which interconnection cables are necessary to achieve a fully renewable power system in Indonesia. These results help identify the specific interconnections required to meet the electricity demand and distribute the renewable energy supply effectively. In order to validate the results, a sensitivity analysis will be used. In this sensitivity analysis, the capital expenses of the HVDC interconnectors will in one case 10% higher and in the other case be 10% lower. This analysis will only be done for the low fluctuating predicted demand scenario. Through analysing these results, this study will demonstrate how sensitive the model is to the variation of this parameter. The results will be discussed in section 6.

4.4 GIS - Geographical Input Data

QGIS, a Geographic Information System (GIS) software, will be used to explore the geographical feasibility of the interconnection lines generated by the Calliope model. As described, there are often arguments on why Indonesia would not be suited for inter-island interconnection. One of these reasons is due to the seismic activity and the ring of fire. This study will analyze four critical geographical aspects in order to provide insights into the feasibility of inter-island interconnections in Indonesia. This section will first describe the method of how the four geographical aspects are selected, then how the geographical aspects are translated to weights for analysis and lastly, how the aspects are analysed. This methodology is based on previous submarine power cable routing studies done by N.Makrakis et al. and Q. Wang et al. [Makrakis et al., 2023, Wang et al., 2019]. The selected geographical features are water depth (bathymetry), seismic regions, seabed inclination, and no-go zones (protected/marine/fishing zones).

4.4.1 Literature study - Critical criteria

In section section 5, a literature review is performed to select the geographical features that are most relevant for submarine power cables between the islands of Indonesia. The selection of the literature that is used for this literature review is done through the use of the program Scopus. Using this tool, a search query is created using the core concepts and keywords of the topic. This query looks like this:

> "Submarine" OR "HVDC" AND ”Interconnection” OR "Cable"

Moreover, to ensure that the articles in this review are relevant and up to date on this fast-developing topic, only articles from the past 5 years are included. Moreover, due to ’snowballing’ articles outside this query are added mainly from the references list of the included articles. The number of articles that are found after these requirements can be found in the following Table 4.2. From this literature study, the most mentioned and relevant features will be selected.

4.4.2 Input data gathering

The next step of gathering the GIS input data is to search for data sets that will be used as representations of the features and used in the GIS model. These selected features are water depth (bathymetry), seismic regions, seabed inclination, and no-go zones (protected/marine/fishing zones). The data for these maps are retrieved from official GIS data providers like governments and the united nations. And overview of the found representation data sets and their sources can be found in section 5.

Limitations	Number of articles
"Submarine" OR "HVDC" AND ”Interconnection” OR "Cable"	59
Exclude articles written before 2018	30
Exclude articles that do not include design aspects	4
Snowballing	3
Total	7

Table 4.2: Search method submarine cable design

4.5 GIS - Determination of criteria weights

The geographical features that are found to influence the cost-effectiveness of the inter-island interconnections can visually be seen in the GIS software. However, in order to analyze and compare these features, the geographical features are translated into categories. The categorization of the geographical features is based on the literature study of the previous section in which various studies on cable routing are analyzed [Wang et al., 2019, Makrakis et al., 2023]. With the categories in place, Analytical Hierarchical Process (AHP) is used to prioritize the criteria on their relative importance. AHP is a method that is commonly used in multi-criteria analysis and consists of the following steps: (1) Gather criteria and organize them into a hierarchy, (2) Compare all criteria to determine relative importance, (3) assign weights to the criteria based on the importance. This means that all the features have criteria connected to them that indicate the impact on the route in categories [Saaty, 2004].

Next, the geographical feature maps are modified into simpler maps to only visualize the chosen categories. So for example, the categorization of the seabed inclination is set to three categories, so the geographical feature map in QGIS only contains these three colours. Then, the simplified geographical feature maps are transformed into a graph representation based on the colours of the pixels in the map, using Python. Every pixel is translated to one node. Then, the weights for each graph representation of the feature maps are added to the nodes. Lastly, the weighted graph representation maps are merged into a map that is a sum of all the weights of the four graph representations.

4.6 Analytical Hierarchical Process (AHP)

This section describes the process of AHP more in-depth. As explained, the AHP method for multi-criteria analysis is first introduced by Saaty [Saaty, 2004]. This method enables the comparison of multiple criteria even though the criteria are different [Saaty, 2004]. This method is widely used in the field of multi-criteria decision-making and hence also in infrastructure design. Specifically for the design of submarine cable routing, a study done by Wang et al. sets an example for using AHP in route design. This study is adopted by Makrakis et al., which is the inspiration for this method in this study [Makrakis et al., 2023].

First of all, the AHP comparison matrix is formulated (Equation 2), in which the criteria (Ci (i = 1,2,3. . . ,), represents the criteria in the equation) are the adopted criteria. In the equation is n the number of criteria and ij a ranking score assigned to each criterion in terms of its importance, using an evaluation scale from 1/9 to 9. This scale is created by Staaty and the explanation can be found in the appendix section 10.3 [Saaty, 2004].

$$[A] = [a_{ij}] = \begin{array}{c|cccc|} & C_1 & C_2 & \dots & C_n \\ \hline C_1 & 1 & \alpha_{12} & \dots & \alpha_{1n} \\ C_2 & \alpha_{21} & 1 & \dots & \alpha_{2n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & \alpha_{n1} & \dots & \dots & 1 \\ \hline \end{array} \qquad i, j = 1,2,3 \dots, n \tag{2}$$

The second step is to compare the criteria pairwise. These are then summed to normalize the criteria, which is mathematically visualized in the following Equation 3

$$[\bar{A}] = \left[\frac{a_{ij}}{\Sigma_k}\right] = \begin{array}{c|cccc|} & C_1 & C_2 & \cdots & C_n \\ \hline C_1 & \frac{a_{11}}{\Sigma_1} & \frac{a_{12}}{\Sigma_2} & \cdots & \frac{a_{1n}}{\Sigma_n} \\ C_2 & \frac{a_{21}}{\Sigma_1} & \frac{a_{22}}{\Sigma_2} & \cdots & \frac{a_{2n}}{\Sigma_n} \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ C_n & \frac{a_{n1}}{\Sigma_1} & \cdots & \cdots & \frac{a_{nn}}{\Sigma_n} \\ \hline \end{array} \quad i,j = 1,2,3\ldots,n. \tag{3}$$

The last step is then to calculate the weight (W), which determines the importance of the criteria in the multi-criteria analysis (Equation 4).

$$\{W\} = \overline{W_i} = \sum_{j=1}^{n} \overline{a_{ij}} \qquad i,j = 1,2,3\ldots,n. \tag{4}$$

The actual weight of each pixel in each geographical feature weight map is determined by multiplying the AHP weight by the weight of the criteria. The weight of the criteria is an integer from a ranking from 1 to 5, which is adapted from the study [Makrakis et al., 2023]. These ranking weights will be multiplied by the AHP weight, which results in the weights that are used in the graph representation of each geographical feature.

4.6.1 Scenarios

The AHP method is chosen to attach the weights to the geographical features since this makes it easy to create different scenarios based on prioritisation. This allows this study to provide the 'optimal' cable route under different scenarios. For this study, two scenarios are selected. The first scenario is a 'minimize risk' scenario, in which the weights for seismic activity and seabed inclination are prioritized. Since these features are expected to be the biggest risk in laying and maintaining the submarine cables [Wang et al., 2019]. The second scenario is the 'minimize costs' scenario, in which the weights for all features are minimal since this will most likely result in the shortest length of the cable route. For these two scenarios, a comparison matrix will be created, using the data from the study by Wang et al., in which the comparison values are based on submarine cable engineering experts [Wang et al., 2019].

4.7 GIS - Analysis

The last step of the GIS analysis is the determination of the shortest path between the islands that should be interconnected. The shortest path will be based on the weights that are connected to each node of the merged graph representation of the geographical features map, as explained in the previous section. This section will explain the algorithm that is used to find the shortest path, and which metric is chosen to analyse the result of the shortest path.

4.7.1 Dijkstra Shortest Path Analysis

As described, the geographical features are transformed into a graph representation [Makrakis et al., 2023]. The method to find the optimal route between two points in this map is through 'shortest path analysis'. Through this method, the route using the least amount of weights is aimed to be found. The algorithm chosen to perform this shortest path determination is Dijkstra's algorithm. This algorithm is chosen for two reasons, first of all since the Dijkstra algorithm is that the implementation of Dijkstra is one of the fastest algorithms to find the shortest path [Zeng and Church, 2009]. Moreover, since the Python package in which the geographical feature map is created, has an already existing function of the Dijkstra algorithm

[NetworkX, 2023]. The Dijkstra algorithm can be implemented in different ways but in this study, the function 'shortest_path' is used.

The Dijkstra algorithm starts with selecting a start and end node. Then the algorithm starts at the start node. From here, the algorithms analyse all the distances to the nodes that neighbour the start node. The neighbour that has the lowest weight will be selected after all neighbouring notes are analysed. Then the selected neighbouring node with the lowest distance will become the new start node and the process starts again. Once a node has been the start node, it will not be selected again. This process is repeated until the end node is reached [NetworkX, 2023].

This chapter explains the methodology used for techno-economic optimization, including both the Calliope model and GIS analysis, in conjunction with the AHP shortest path analysis. These methods are combined to offer a more comprehensive analysis than their individual application. The subsequent chapter will present the outcomes resulting from this methodology.

5 Planning and design criteria for HVDC submarine cables

This section describes the content of several studies found in which submarine cable routes are designed and explored. All studies focus on cost-optimization and consideration of geographical features that influence the feasibility of the implementation of the submarine cable (subsubsection 5.0.1). Then the most important geographical feature will be selected (section 5). Eventually, these geographical features will be discussed for Indonesia in subsection 5.1.

5.0.1 Submarine cable design criteria

A recent study by Mircea Ardelean demonstrates a method to assess the suitability of shores for submarine power interconnections [Ardelean and Minnebo, 2023]. In this study, four factors are chosen to play a crucial role in determining a suitable location for interconnection. The first factor that is crucial in submarine power interconnections is the depth of the water that the cables will cross. This is important since implementation in deeper waters is more expensive and up until now some depths are not yet economically feasible. Then, the distance between the two shores is also an important factor. Not only is a longer cable more expensive, but longer cables also cause more loss of electricity in transportation. For instance, the trans-Atlantic cable (3300 km), is expected to have a power loss of 9% in transmission whereas on-land transmission power loss normally stays under 2%. Then, to assess whether a location is a good fit for submarine interconnection, it is important to consider the aspects of the to-be-connected shores. In this category, the demand for electricity on shore is important to determine where the interconnection should be placed. One indicator of this factor is the population density of the shore, a high population density usually means a high electricity demand and relatively many sub-stations [Ardelean and Minnebo, 2023]. Moreover, next to demand, the interconnectors should be positioned in areas where there is a high potential for RET since this is where the electricity is generated.

In an article by Gordonnat [Gordonnat and Hunt, 2020], the challenges and critical aspects of submarine interconnection are explored. In this case, applied to a connector between Australia and Singapore. In this publication, the optimal marine routes of the submarine cables are determined. The anticipated marine route aims at minimising the overall cable length whilst avoiding unnecessary deep water and steep-sloped sections between Australia and Singapore. From this article various design aspects are described that should be considered while designing a marine route for the submarine cables. First of all, the seabed congestion level, avoiding crossing a large number of existing pipelines and communication cables, and protection against damage from fishing activities that will necessitate the cables being trenched or protected by alternative means over an extended route length. Moreover, protect the cables against anchor damage and navigation hazards. Further, consider that the current through a single HVDC cable in shallow waters may create navigation compass deviations by passing vessels. Seismic regions should be avoided to prevent cable damage. Since deep water instalment is more expensive, so try to avoid this.

Another article that describes the design process of submarine power cables is by Ichimura [Ichimura and Omatsu, 2019], the following steps are taken for the route design. First of all, the connection points are identified. Then the second step is the creation of optimal routes and these are evaluated. The last step is the calculation of the costs, for each route. Within the second step, the determination of optimal routes, the factors of water depth, seabed complexity and fishing grounds are considered.

Itiki analyses the technical feasibility of a HVDC cable between Japan, Taiwan and the Philippines [Itiki et al., 2020b]. The design of this route is constrained by three factors, the maximum water depth of 3 km, avoidance of fisheries and protected marine areas [Itiki et al., 2020b].

In Ardelean's report on the state-of-the-art of submarine HVDC power cables, the following aspects of route design are identified [Ardelean and Forename, 2015]. The water depth is an important constraint, up till now the cables are mainly laid in shallow water, less than 500m deep. There are a few examples of cables going deeper than this but this one does not happen often. The seabed topography is also an important factor, the routes should avoid deep trenches and steep slopes while maintaining the shortest path. The hydrostatic pressure should be considered for deeper cables.

A study carried out by Makrakis and Tsonoanakis on the optimal route selection for submarine cables used a multi-criteria decision tool to analyse the optimal geographical route of submarine cables [Makrakis et al., 2023]. GIS software is used to provide this data. The chosen criteria that the tool considers are seabed inclination, bathymetry and seismic fault zones.

Lastly, a study performed by Wang, determined a method for cost-effective path planning for submarine cable network extension [Wang et al., 2019]. In this paper, the researchers determine all factors that should be considered in submarine route design. These factors are then attached to a weight to demonstrate their importance to the design. The factors considered are water depth, earthquakes, volcanic eruptions, seabed slope, sediment hardness, minimize essential construction cost, marine zones, fishing zones and anchoring zones.

The following Table 5.1 summarizes the design requirements found in the previously discussed articles.

Table 5.1: Overview of requirements for the design of submarine cable routes found in literature

Article	**Year**	**Route**	**Minimize lenght**	**Avoid deepwater**	**Connect to high demand**	**Connect to RET potential**	**Seabed Inclination**	**Avoid seismic regions**	**Avoid congestion**	**Avoid protected areas**	**Avoid high pressure**
The suitability of seas and shores for building submarine power interconnections [Ardelean and Minnebo, 2023]	2023	Not specified	X	X	X	X					
GIS-Based Optimal Route Selection of Submarine Cables Considering Potential Seismic Fault Zones [Makrakis et al., 2023]	2023	Multiple in EU	X	X			X	X			
Subsea cable key challenges of an intercontinental power link: case study of Australia-Singapore interconnector [Gordonnat and Hunt, 2020]	2020	Australia-Singapore	X	X			X	X	X		
Technical feasibility of Japan-Taiwan-Philippines HVdc interconnector to the Asia Pacific Super Grid [Itiki et al., 2020b]	2020	Japan, Taiwan, Philippines	X	X						X	
Route designs and cost estimation for Japan Russia and Japan, South Korea interconnections [Ichimura and Omatsu, 2019]	2019	Japan-Russia, South Korea	X	X	X		X			X	
Cost-Effective Path Planning for Submarine Cable Network Extension [Wang et al., 2019]	2019	Not specified	X	X			X	X		X	
HVDC Submarine Power Cables in the World State-of-the-Art Knowledge [Ardelean and Forename, 2015]	2015	Not specified		X			X	X		X	X

5.0.2 Selected GIS requirements for submarine cable design

As the overview in Table 5.1 shows, the described studies share several common aspects regarding the planning and design of submarine cables. These include the minimization of the cable length and so cost while considering the factors of water depth (bathymetry), seismic regions, seabed inclination, and protected/marine/fishing zones. Data sets that represent these geographical features in a GIS format are found and gathered from the sources as listed in the following Table 5.2.

Table 5.2: Dataset and sources for the GIS model

Dataset	Source
Bathymetry	GEBCO Compilation Group [GEBCO Compilation Group, 2023]
Seabed Inclination	Calculated from Bathymetry in QGIS [GEBCO Compilation Group, 2023]
Seismic regions	United States Geological Survey [USGS, 2022]
No-go zones	United Nations List of Protected Areas [UN, 2023]

5.1 Categorization and description of selected geographical features

As determined in the previous section the four geographical features water depth (bathymetry), seismic regions, seabed inclination, and protected/marine/fishing zones are selected as important for the design of submarine cable routes. This section will further describe why the features are important, based on the reviewed literature. Secondly, this section will organize the features into categories, based on the reviewed literature. Finally, this section will briefly discuss the challenges associated with each geographical feature, offering some interpretation of the optimization process in the next chapter.

5.1.1 Bathymetry

The depth of water where submarine power cables are installed is an important factor. Deeper waters make the installation more expensive and less economically feasible [Ardelean and Forename, 2015]. It also makes it harder to manoeuvre the trench-cutting equipment and recover the cables. Deep-water conditions increase the hydrostatic pressure and add complexity to the service. Having accurate knowledge of water depth is crucial for optimizing costs and ensuring the effective functioning of the cables [Ardelean and Minnebo, 2023]. By planning the cable path through shallower waters, we can minimize expenses while maintaining a reliable system. From the reviewed literature, the maximum water depth that can currently be crossed is up to 3000 meters [Makrakis et al., 2023]. However, the deeper the water, the higher the costs. Therefore, the water depth can be split into categories ranging from most convenient, to less convenient:
1) 0 - 100 meters: shallow
2) 100 - 500 meters: average
3) 500 - 1500 meters: deep
4) 1500 - 3000 meters: very deep

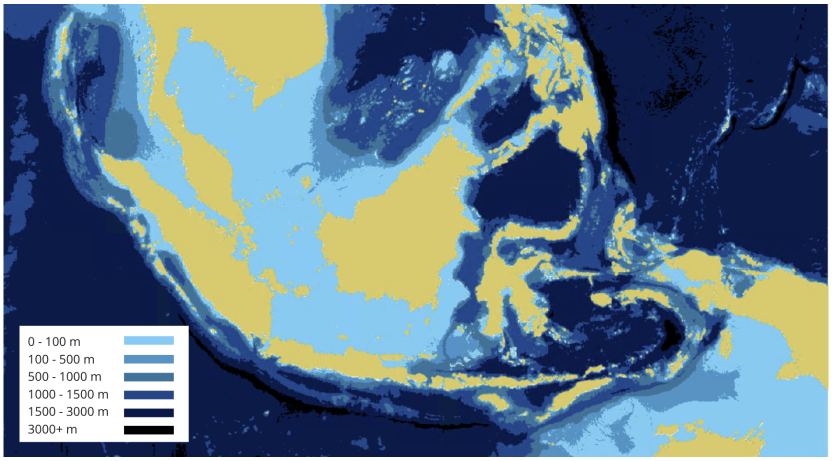


Figure 5.1: Sea depth

As determined, the challenges for HVDC submarine power cables start at sea depths of about 500 meters, ranging to a maximum of 3000 meters. As can be seen in the spatial map of bathymetry, the sea does not reach challenging depths between Sumatra, Java, and Kalimantan. However, in between Kalimantan and Sulawesi, the sea reaches challenging depths for HVDC submarine power cables. Moreover, between Sulawesi and Nusa Tenggara, certain areas also fall into the challenging category.

5.1.2 Seabed inclination

The seabed inclination refers to the slope of the seabed in a particular area. Submarine power cables encounter challenges when dealing with steep slopes [Wang et al., 2018]. Firstly, high slopes can put stress on the cables themselves. Secondly, special machines are used to bury the cables under the seabed, and these machines face difficulties operating in uneven seabed conditions. Generally, seabed slopes can be classified into three categories based on their impact [Makrakis et al., 2023]:
1) 0 - 10 degrees: No significant problems are expected.
2) 10 - 20 degrees: Slopes in this range can cause some issues during cable laying.
3) 20+ degrees: Steeper slopes present major challenges.

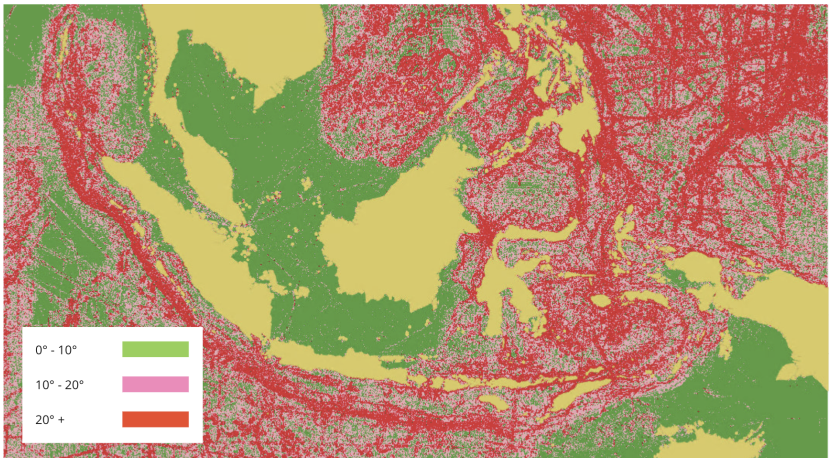


Figure 5.2: Sea bed slope

As determined, the slope of the seabed becomes a big challenge related to HVDC submarine power cables when a slope higher than 20 degrees is present on the seabed. In the sea between Sumatra, Java, and Kalimantan, there are a few small areas in which the slope reaches a degree between 10 and 20, which can cause problems but has been done in historical submarine HVDC projects. The sea between Kalimantan and Sulawesi does contain multiple lines of high seabed slope. This is also the case for the sea between the islands of Nusa Tenggara itself and between Sulawesi.

5.1.3 Seismic regions

Seismic regions are a risk for damage to the submarine power cables [Makrakis et al., 2023]. Volcanic eruptions can damage submarine cables through lava flows and avalanches of hot debris directly. Earthquakes can result in significant displacements of the seabed and destabilization of the seabed sediment by surface faulting and landslides which can potentially damage submarine cables [Ichimura and Omatsu, 2019].

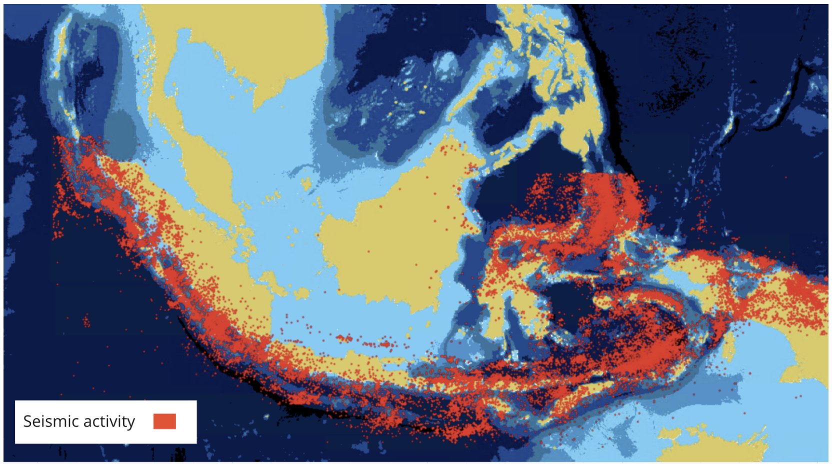


Figure 5.3: Seismic regions

The seismic activity can mainly be found in the so-called 'ring of fire', this ring is located outside of Indonesia's national seas, south of Sumatera, Java and Nusa Tenggara. However, in this spatial view, it can be seen that there are a few areas within the national seas that should be taken into consideration when selecting HVDC submarine cable routes. Especially in front of the coast of Java and surrounding the islands of Sulawesi.

5.1.4 Protected/marine/fishing zones

To ensure the reliability and integrity of submarine power cables, it is essential to avoid environmentally sensitive regions as much as possible [Wang et al., 2018]. Fishing activities and anchoring are two primary causes of cable faults, often resulting from fishing equipment or accidental anchor damage. Therefore, it is crucial to minimize the presence of cables in these areas to mitigate the risks associated with fishing and anchoring activities. By avoiding these zones, the likelihood of cable damage can be significantly reduced [Ardelean and Forename, 2015].

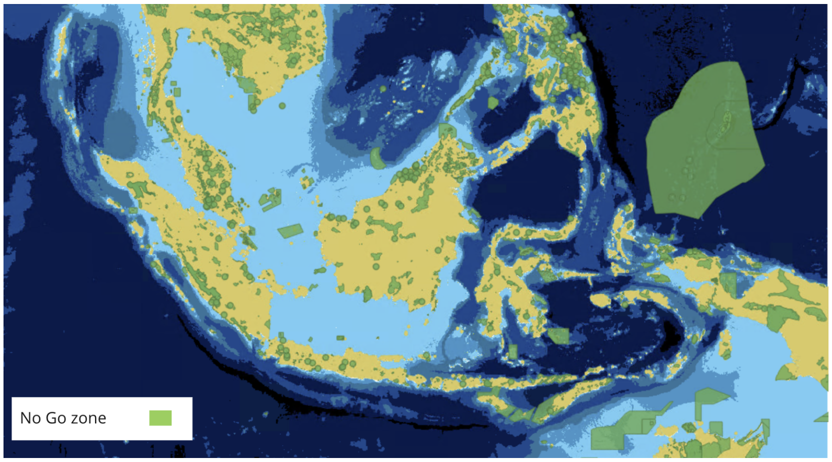


Figure 5.4: No-go zones

The protected sea areas that should be avoided for the HVDC submarine power cables routes are located in the sea between Sumatra and Kalimantan, between the smaller islands in Nusa Tenggara and in front of the coast of Java.

This chapter described the selection results for the geographical features that are crucial to include in the GIS analysis of submarine power cable design. Moreover, it demonstrated the categorization of the threshold values within the individual geographical features. These results will serve as vital inputs for the forthcoming GIS analysis and AHP shortest path analysis, which will be discussed in the following chapter.

6 Techno-Economic Optimization: Results and Analysis

This chapter describes the results for the techno-economic optimization following the method as described in section 4. The first section will describe the results and reasoning for changes in the next iteration for both scenarios (subsection 6.1). Then, a sensitivity analysis is performed in (subsection 6.3). Finally, the determined interconnections are given as input to the AHP shortest path algorithm, the results of the determined routes can be found in subsection 6.4.

6.1 Power system optimization in Calliope

6.1.1 First iteration - low fluctuation scenario

The first Calliope optimization is performed for the two scenarios following the method described in subsubsection 4.2.1, the low fluctuation and the high fluctuation scenario. For this first run, all possible interconnections between two neighbouring islands are allowed, whereas the Calliope model selects the necessary interconnections. The results of the run can best be seen as a visual figure. The following Figure 6.1 and Figure 6.2 show the maximum necessary capacity of the chosen interconnections after the Calliope optimization. The maximum capacity is the highest necessary power that needs to be transmitted through the interconnection at any given moment in time, the unit for maximum capacity is in MegaWatt (MW). Using a scale of colours, the figure shows which interconnections have a high maximum capacity and which interconnections have a low maximum capacity.

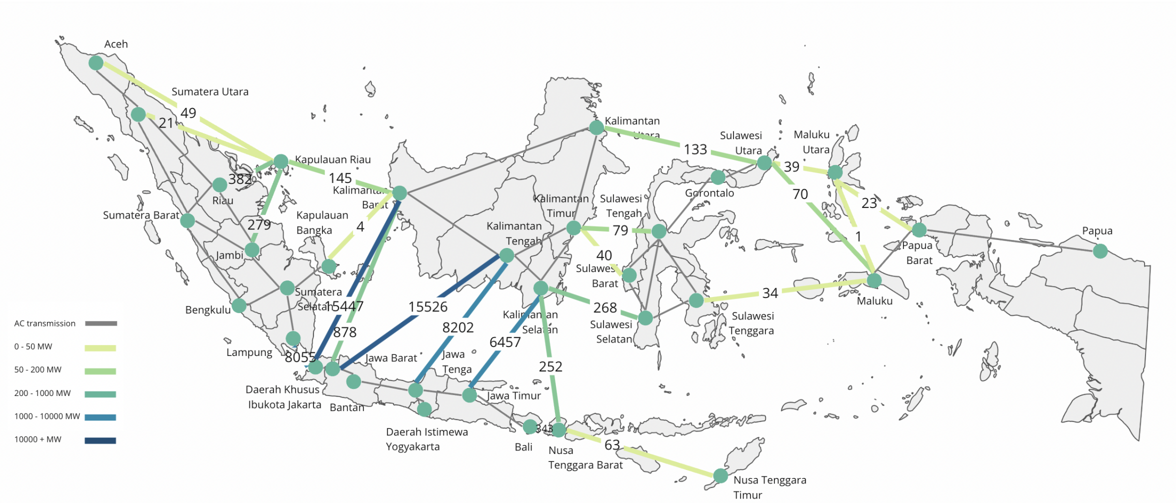


Figure 6.1: Maximum capacities of selected interconnectors in MW for the first iteration of the Calliope optimization under the low fluctuation demand scenario in 2050

As can be seen in the figure, there is a significant difference between the maximum capacities of different interconnection cables in this optimization. Whereas, the highest capacity is 15526 MW, the lowest is as low as 4 MW. Since the amount of power transmitted is related to the unbalance between the two neighbouring islands, the responsibility of the high-capacity interconnections is higher than the lower ones. As explained in section 3, HVDC cables start to make reasonable sense from about 500 MW. Therefore, the first insight from this first iteration is that a part of the used interconnections are of such a small size that it would not make sense to include them in the system due to the high price of constructing the interconnection. Therefore, the low fluctuation informs this study that multiple interconnections are not feasible on the argument of needed capacity versus construction price. Therefore, all interconnections that have a maximum power of 100MW or less, should be removed in the next iteration.

Moreover, this optimization shows that significantly the most capacity is needed between the provinces of Java, Kalimantan and Sumatra. The direction of transmission is from Kalimantan and Sumatra towards Java.

6.1.2 First iteration - high fluctuation scenario

The following Figure 6.2 shows the results after the first iteration of the second scenario, using the demand scenario with high fluctuations. The same colour scale is used to show the different maximum capacity numbers for the different interconnections.

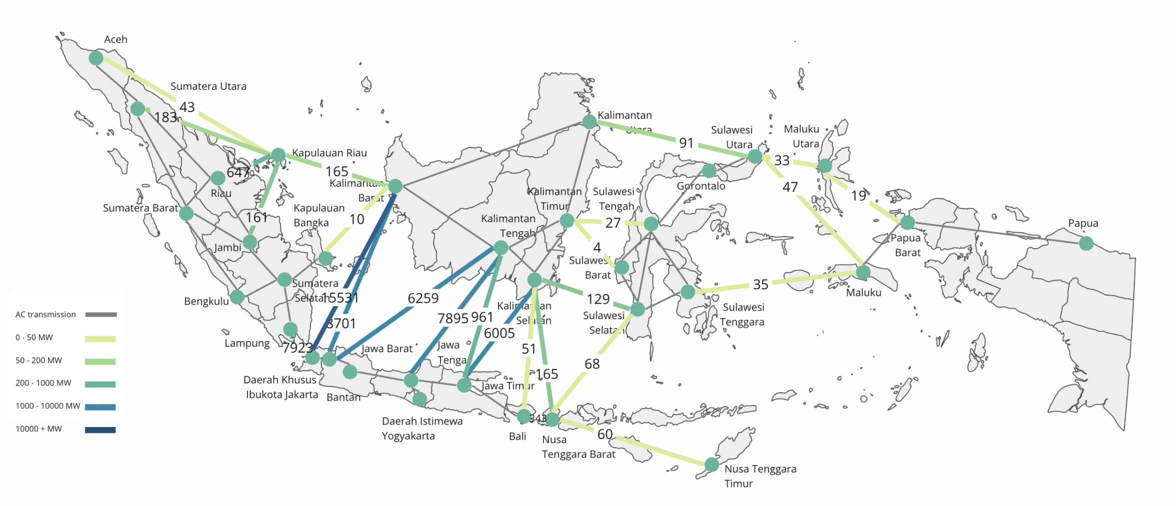


Figure 6.2: Maximum capacities of selected interconnectors in MW for the first iteration of the Calliope optimization under the high fluctuation demand scenario in 2050

As can be seen in the figure, the transmission capacities are higher in this scenario for most interconnections. Moreover, two extra interconnections are used between Kalimantan and Java. An interesting aspect here is that the biggest interconnector from the low fluctuation scenario of 15526 MW has significantly decreased for this optimization to 7896 MW. Moreover, all the interconnections in the Maluku provinces have a lower maximum capacity than in the low fluctuation scenario. Next to these differences, the same insight can be drawn from the high fluctuation scenario that a set of interconnections has such a lower maximum capacity that their construction would not be feasible. Therefore, these will be removed from the second iteration.

6.1.3 Second iteration - low fluctuation scenario

The following Figure 6.3 shows the results for the second iteration of the Calliope model optimization. For this second iteration, as described, the non-feasible lines that are used for a significantly low capacity are removed from the model.

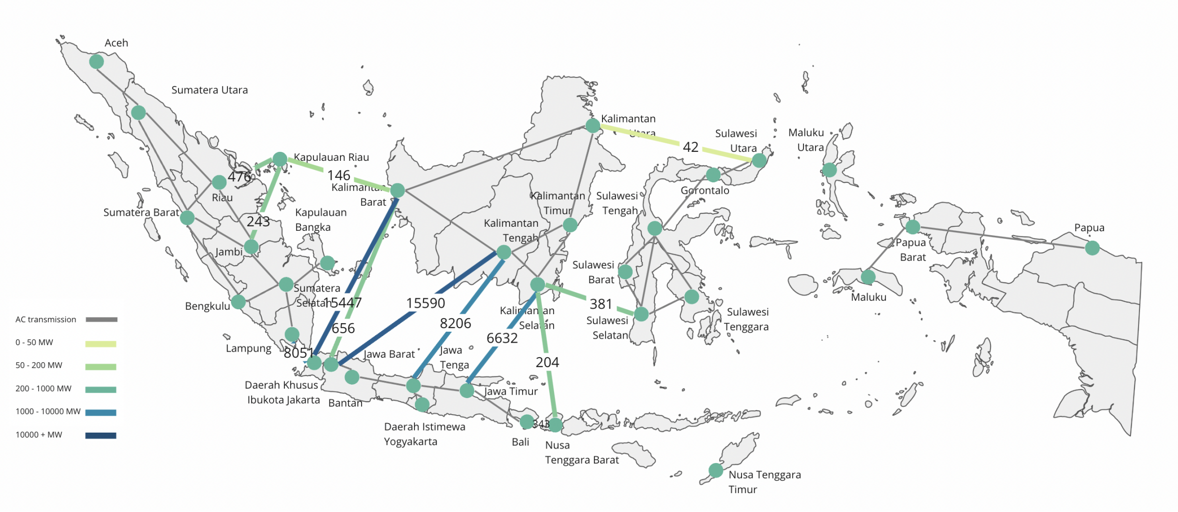


Figure 6.3: Maximum capacities of selected interconnectors in MW for the second iteration of the Calliope optimization under the high fluctuation demand scenario in 2050

As can be seen in the model, the interconnections that were most dominant in the first iteration, are still the most dominant in the second iteration. However, now the options of the interconnections are limited for the model, the optimization decision is made to not use two of the interconnections that were used before. Moreover, the interconnector between Kalimantan Utara and Sulawesi Utara (right-top), is used for a lot less capacity than in the first iteration, the capacity of this interconnector even goes under the threshold of 100 MW. Therefore, this interconnector will be excluded from the next iteration.

The interconnections between Java, Kalimantan and Sumatera carry the highest power capacity in the system. Kapulauan Riaua is a highly connected province as well in this model, connecting to other Sumatera provinces and Kalimantan. However, as described in Figure 5.4, there is a large protected area on this line. This protected area is called Kabupaten Bintan and is protected to maintain coral reefs and biodiversity in the seas close to the Kapulauan Riaua islands [UN, 2023]. Given this insight and the fact that the required transmission capacity of this interconnector is only 145 MW, just above the set threshold of 100 MW, this interconnector will be removed in the next iteration.

The interconnector between Kalimantan Selatan and Sulawesi Selatan crossed deep water, between the 1000m and 1500m. Moreover, this cable crosses multiple areas in which the interconnector crosses a major challenging sea bed inclination of more than 20 degrees. Therefore, this interconnector will be removed from the next iteration. For similar reasons, the interconnector between Bantan (Java) and Lampung (Sumatera), will also be removed due to steep seabed inclination and high seismic activity. Lastly, the interconnector between Bali and Nusa Tenggara Barat crosses an area that is completely covered in seismic activity and major challenging sea bed inclination. Therefore this interconnector will also be removed.

Moreover, as can be seen in Figure 6.3, there are multiple interconnections between the provinces of Java and Kalimantan. Whereas this makes sense from the optimization in Calliope, where the cost for interconnection is calculated per MW and MWh, from the literature analysis, this study found that the construction time and purchase costs of the HVDC interconnections are disadvantages of using the technology. With this reasoning in mind, the interconnector between Jawa Barat and Kalimantan Barat will be removed. Moreover, the interconnector between Nusa Tenggara Barat and Kalimantan Selatan will also be removed in the next iteration. Lastly, since Jambi and Riau are already connected through AC on-land transmission, one of these interconnections will also be removed to reduce the amount of construction that will have to be performed. Since Riau had a closer distance to Kapulauen Riau, this interconnector will stay, the other one will be removed.

6.1.4 Second iteration - high fluctuation scenario

The following Figure 6.4 shows the results for the second iteration of the Calliope model optimization under the highly fluctuating predicted demand scenario. For this second iteration, as described, the non-feasible lines that are used for a significantly low capacity are removed from the model.

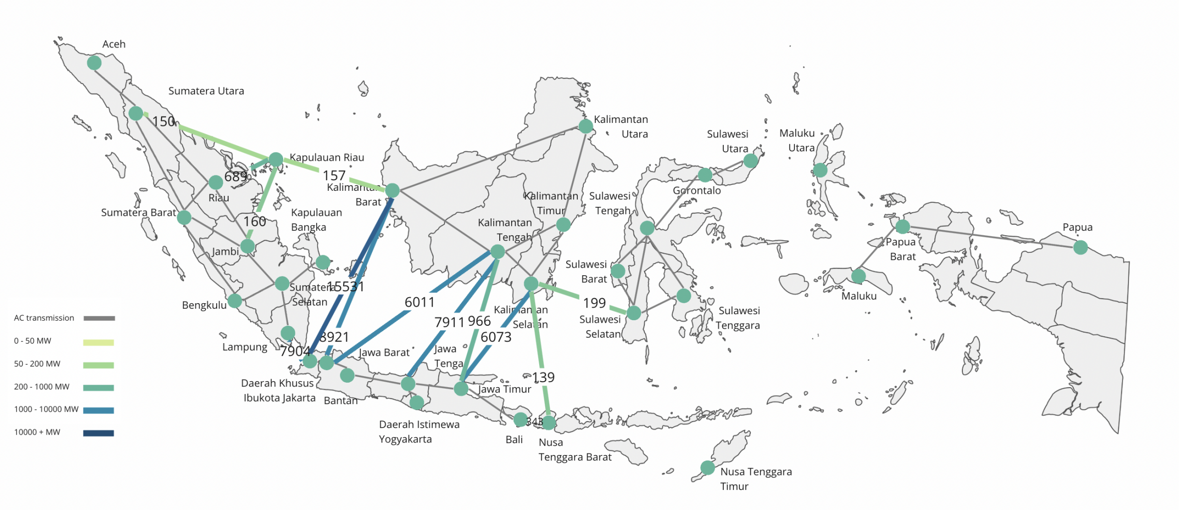


Figure 6.4: Maximum capacities of selected interconnectors in MW for the second iteration of the Calliope optimization under the high fluctuation demand scenario in 2050

The analysis of this result is similar to the analysis of the second iteration of the low-fluctuating scenario. As can be seen in the Figure 6.4, the most prominent capacity interconnections are still between the same provinces as in the first iteration. However, the required transmission between Sulawesi Selatan and Kalimantan Selatan is slightly higher than in the first iteration. Moreover, two of the three interconnections from Riau Kapulauen to Sumatera have an increased power rating. Whereas the third one is similar to the previous iteration.

The as mentioned in the previous analysis of the second iteration of the low-fluctuating scenario, the interconnector between Kapulauen and Kalimantan Barat strikes a large protected area on this line. This protected area is called Kabupaten Bintan and contains protected seas, coral reefs and biodiversity [UN, 2023]. Therefore, this interconnector is considered not feasible and will be removed.

As previously described, due to the highly expensive construction costs of HVDC transmission, this study favours the use of fewer interconnections between neighbouring islands. Therefore, when multiple interconnections are used between two islands, the interconnections with the lower needed capacity will be removed. Due to this reasoning, the interconnector between Sumatera Utera and Kapulauan Riau will be removed, also the interconnector between Jambi and Kapulauan Riau. This is possible since the interconnector between Kapulauan Riau and Riau is kept and the latter is connected through AC transmission to the other two aforementioned locations. This same logic is applied to the interconnections between Jawa and Kalimantan, the interconnections between Jawa Timur and Kalimantan Tengah will be removed, as well at Nusa Tenggara Barat and Kalimantant Selatan.

Lastly, as described in the analysis of the low fluctuating scenario, the inter-connector between Kalimantan Selatan and Sulawesi Selatan crossed deep water and challenging seabed slopes. Moreover, the needed capacity for this interconnector is on the lower side of the whole system. Therefore, this interconnector will also be considered as not feasible. For the same reasoning as described in the analysis of the low fluctuating scenario, the interconnector between Bantan (Java) and Lampung (Sumatera) and between Bali and Nusa Tenggara Barat will also be removed due to steep seabed inclination and high seismic activity.

6.1.5 Final result - both scenarios

The following Figure 6.5 and Figure 6.6 shows the results for the last iteration of the Calliope model optimization under the low fluctuating and high fluctuating predicted demand scenario. For this last iteration, as described, the non-feasible interconnectors that use a significantly low capacity and create big challenges from the perspective of geographical features are removed from the model. Moreover, in two cases of a double interconnector from one island to a single province on a neighbouring island with one of these having a relatively low required capacity, the interconnector with the least required capacity is removed.

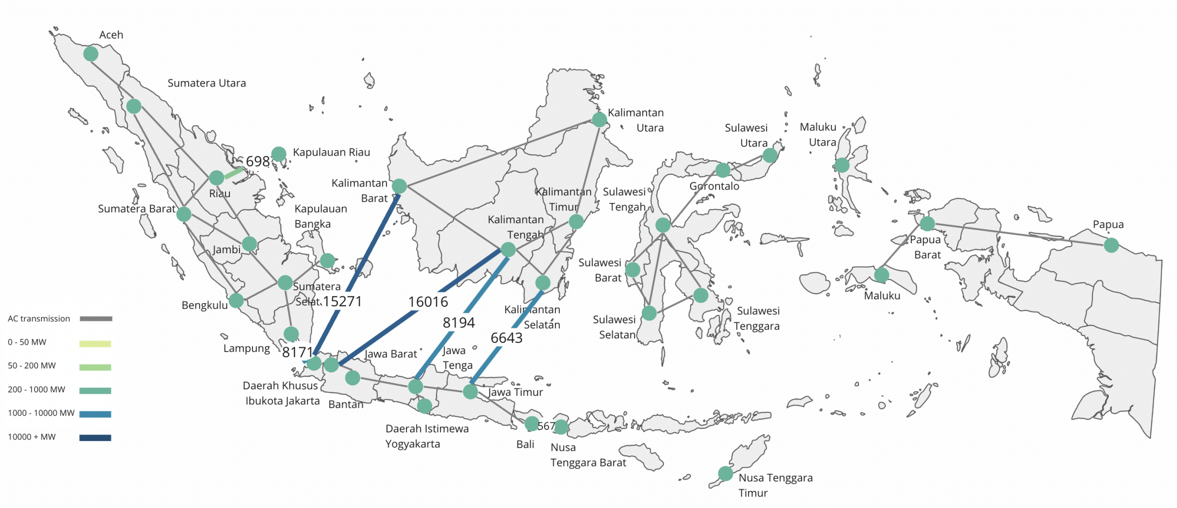


Figure 6.5: Maximum power capacities of selected interconnectors in MW for the final iteration of the Calliope optimization under the low fluctuation demand scenario in 2050

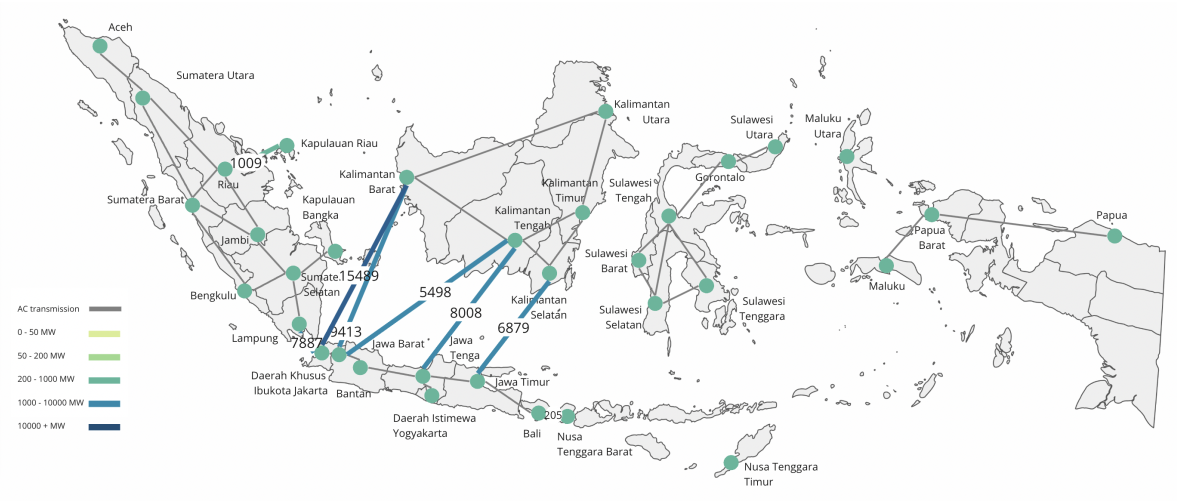
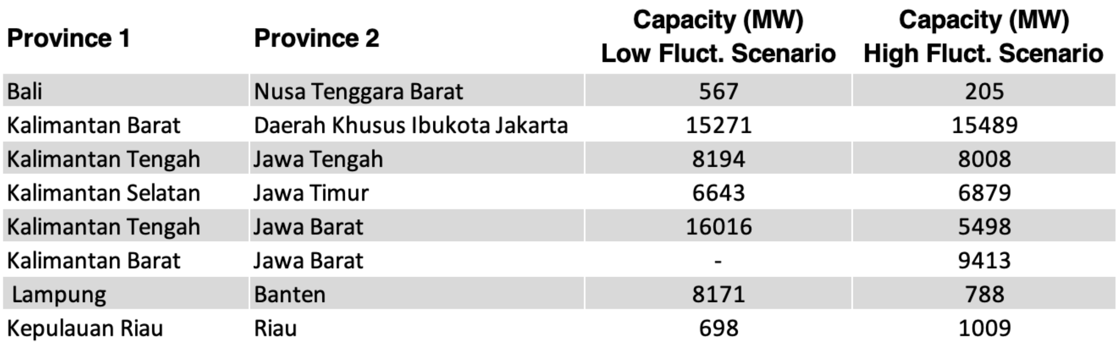


Figure 6.6: Maximum power capacities of selected interconnectors in MW for the final iteration of the Calliope optimization under the high fluctuation demand scenario in 2050

As can be seen in Figure 6.5, there are five interconnection cables left after the last optimization. In Figure 6.6, there are six interconnection cables left. All these interconnections are analysed from the perspective of the identified important geographical features; bathymetry, seabed inclination, seismic regions and protected areas. Moreover, the interconnections all have a power capacity of more than 100 MW and are distributed over the neighbouring islands. The interconnections that are left are feasible following the methodology of this study. An overview of the interconnections with capacities can be found in Table 6.1

Table 6.1: Overview of the feasible interconnections with power capacities for the low and high fluctuating demand scenario



Province 1	Province 2	Capacity (MW) Low Fluct. Scenario	Capacity (MW) High Fluct. Scenario
Bali	Nusa Tenggara Barat	567	205
Kalimantan Barat	Daerah Khusus Ibukota Jakarta	15271	15489
Kalimantan Tengah	Jawa Tengah	8194	8008
Kalimantan Selatan	Jawa Timur	6643	6879
Kalimantan Tengah	Jawa Barat	16016	5498
Kalimantan Barat	Jawa Barat	-	9413
Lampung	Banten	8171	788
Kepulauan Riau	Riau	698	1009

6.2 Single cable configuration

As can be seen in the previous sections, the greatest capacity of feasible interconnections is between the regions of Java and Kalimantan. From this study, it appeared that the sea between Java and Kalimantan is geographically feasible for the interconnections and crucial for the balance of the electricity system. Since the Calliope model is programmed to work with regions, there is an individual submarine cable between each region that needs to be connected in order to be balanced. However, taking an economic perspective, it might be more efficient to choose the regions that are closest to each other, connect these and distribute the electricity on-land between the other regions on an island. Therefore, the following configuration shows the necessary capacity between Java and Kalimantan if the capacity is satisfied through a single connection.

As described in section 3, the usual capacity for HVDC submarine cables is about 1000 MW. Therefore it is worth noting that this single cable configuration does not mean that the connection will be using only one cable. Therefore, when referring to a single cable configuration, it signifies that the required capacity will be accommodated using multiple cables along the same route. For clarity and to illustrate this concept, the analysis focuses on the high fluctuating demand scenario as it represents the highest capacity requirement. The Figure 6.7 below provides a visual representation of the maximum power capacities for selected interconnectors in Megawatt for the single cable configuration under the high fluctuating demand scenario in 2050:

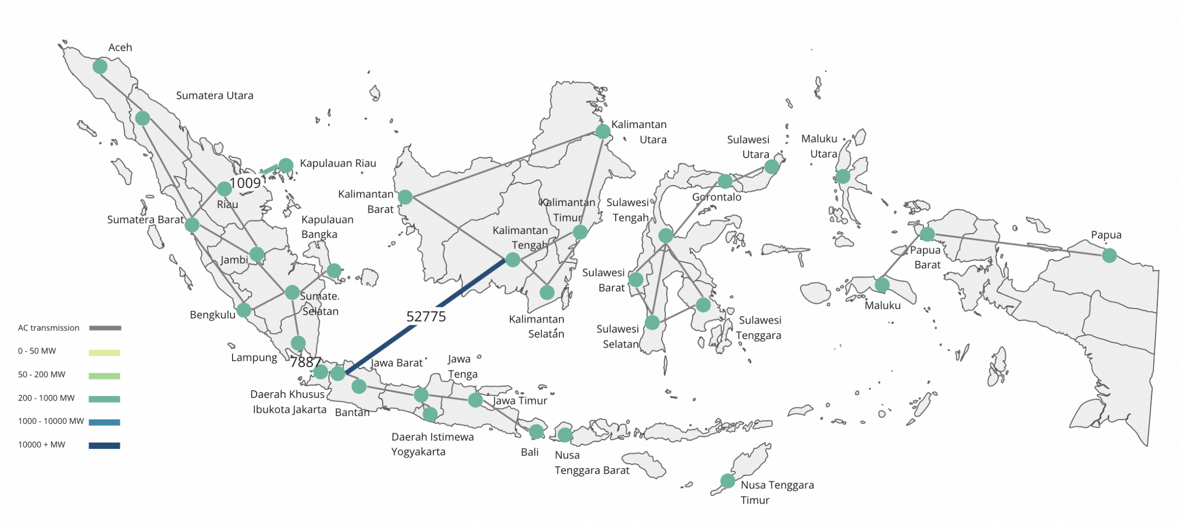
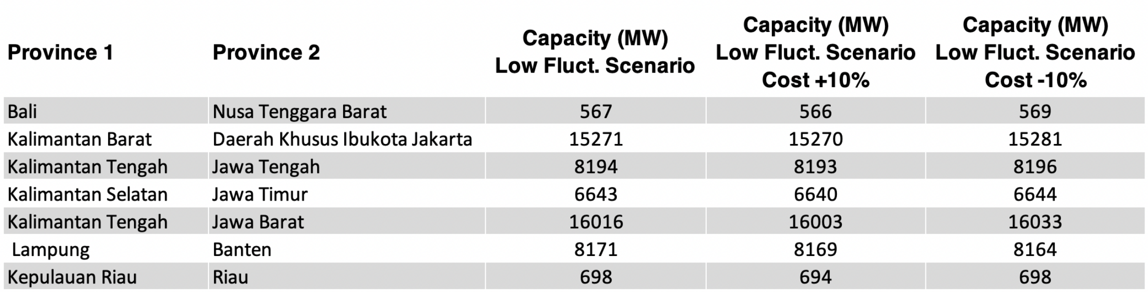


Figure 6.7: Maximum power capacities of selected interconnectors in MW for the single cable configuration of the Calliope optimization under the high fluctuation demand scenario in 2050

6.3 Sensitivity Analysis

The following section shows the result of the sensitivity analysis, as described in subsection 4.3.
The energy capacity costs of the transmission technologies per MW are increased by 10% and decreased by 10% in order to gain insight into the effect of the variation of the cost parameter on the results of the model. The following Table 6.2, shows the results of this analysis.

Table 6.2: Sensitivity analysis of energy capacity costs of HVDC transmission



Province 1	**Province 2**	**Capacity (MW) Low Fluct. Scenario**	**Capacity (MW) Low Fluct. Scenario Cost +10%**	**Capacity (MW) Low Fluct. Scenario Cost -10%**
Bali	Nusa Tenggara Barat	567	566	569
Kalimantan Barat	Daerah Khusus Ibukota Jakarta	15271	15270	15281
Kalimantan Tengah	Jawa Tengah	8194	8193	8196
Kalimantan Selatan	Jawa Timur	6643	6640	6644
Kalimantan Tengah	Jawa Barat	16016	16003	16033
Lampung	Banten	8171	8169	8164
Kepulauan Riau	Riau	698	694	698

As can be seen, the transmission capacity follows the costs of the transmission technology. When these prices are increased by 10%, the transmission capacity is lower. For the other scenario, when the costs of the transmission capacity are decreased by 10%, more transmission capacity is used in the model. However, this is not a linear relationship, the transmission capacity changes less than 1% for both scenarios and all transmission capacities when the costs are changed with 10%. Therefore, the conclusion can be drawn that the costs do directly influence the transmission capacity, but the capacity is also influenced by other factors.

6.4 Routing using AHP and shortest path

This section will describe the results of the shortest path analysis using a combination of the Analytic Hierarchy Process (AHP), graph representation and Dijkstra's shortest path analysis. First, a short summary of the method will be repeated. Then the results of the AHP will be described. Lastly, the Dijkstra shortest path shows will show the shortest paths found in the merged AHP weight map. These results will be further interpreted in the discussion in section 9.

Through the use of a network representation of the colours extracted from the geographical GIS images, the spatial information can be leveraged to generate a weight map. As described, (AHP) is used to enable the comparison of different geographical criteria in one analysis. As described, first a comparison matrix is created for the different scenarios. Then the weight map is created for each geographical feature. Then these maps are merged. This merged weight map is the graphical representation through which the Dijkstra shortest path algorithm is performed. This results in a visual route and the length of the shortest path. The following Table 6.5, shows the result for the AHP weight determination and the category ranking per geographical feature.

6.4.1 AHP comparison matrix

The comparison matrix for each scenario is based on the results of the study by Wang et al., in which the geographical criteria comparisons are developed on a determination of costs and other engineering aspects. The following Table 6.3 and Table 6.4 show the comparison matrix for the two scenarios.

Table 6.3: Comparison Matrix Scenario 1

	Bathymetry (m)	Seabed Inclination (°)	Seismic activity	Protected area	AHP Weight (%)
Bathymetry (m)	1	1/4	1/9	1	7
Seabed Inclination (°)	4	1	1/2	4	28
Seismic activity	9	2	1	9	59
Protected area	1	1/4	1/9	1	7

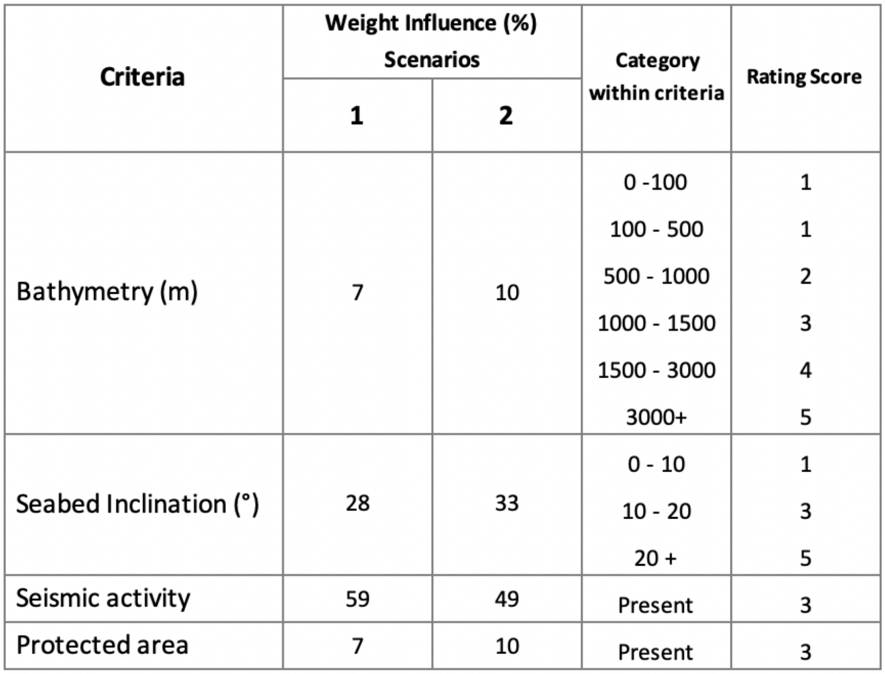
As can be seen in the tables, the first scenario prioritises the avoidance of seismic activity and seabed inclination. The second scenario flattens the difference between the geographical features.

Table 6.4: Comparison Matrix Scenario 2

	Bathymetry (m)	Seabed Inclination (°)	Seismic activity	Protected area	AHP Weight (%)
Bathymetry (m)	1	1/4	1/4	1	10
Seabed Inclination (°)	4	1	1/2	4	33
Seismic activity	4	2	1	4	47
Protected area	1	1/4	1/4	1	10

The use of the two AHP comparison matrices will determine the weights attached to the geographical features in the shortest path analysis. The following Table 6.5 shows the criteria with the weight influence for each scenario in percentage and the ranking scores per geographical feature category.

Table 6.5: AHP analysis weights and ranking score in the two different scenarios



Criteria	**Weight Influence (%) Scenarios**		**Category within criteria**	**Rating Score**
	1	**2**		
Bathymetry (m)	7	10	0 -100	1
			100 - 500	1
			500 - 1000	2
			1000 - 1500	3
			1500 - 3000	4
			3000+	5
Seabed Inclination (°)	28	33	0 - 10	1
			10 - 20	3
			20 +	5
Seismic activity	59	49	Present	3
Protected area	7	10	Present	3

6.4.2 Shortest path results

The Figure 6.8 and Figure 6.9 display the shortest path for an HVDC interconnector based on the four geographical features weighted through AHP under the first scenario and the second scenario. The displayed interconnections are the required interconnections as found in the first part of this chapter.

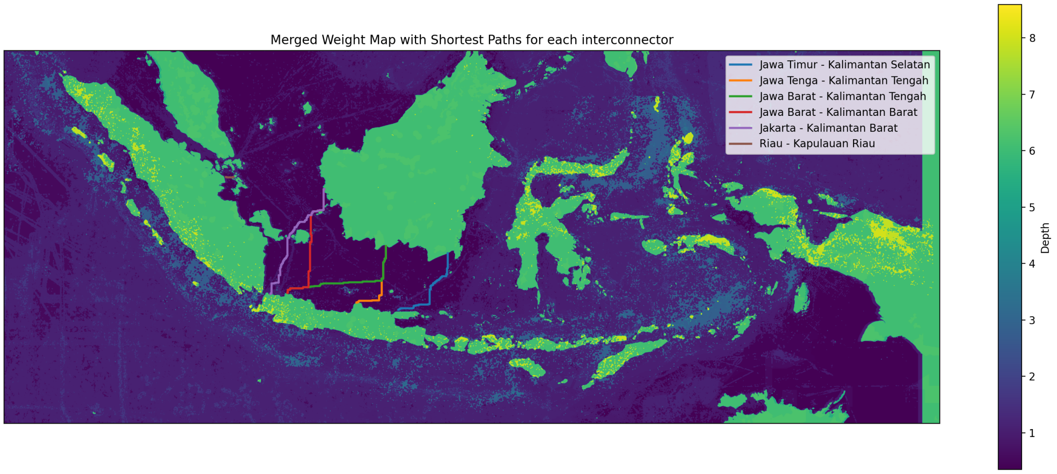


Figure 6.8: Output Dijkstra shortest path in AHP merged weighted map, under comparison matrix of scenario 1

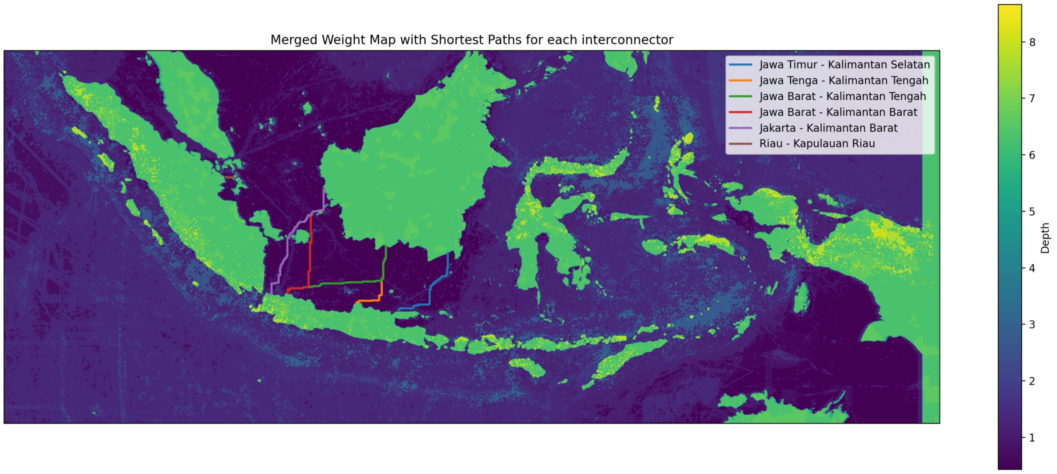


Figure 6.9: Output Dijkstra shortest path in AHP merged weighted map, under comparison matrix of scenario 2

As can be seen in the figures, there is no visible difference between the two scenarios. The shortest paths for the interconnections have the same route whether the seismic activity is prioritized or not. What can be drawn from the figures is that in some parts of the interconnector routing, specific parts get avoided. For instance, the interconnector between Jawa Timnur and Kalimantan Selatan has a crooked shape. This can be explained by some lines of high seabed inclination that are present in the linear line between these provinces.

This chapter demonstrates the results of the techno-economic optimization. These results include the necessary interconnection capacities determined by the Calliope model, their interpretation, the removal of infeasible interconnections during iterations, and the results of the AHP shortest path analysis. Furthermore, this chapter illustrates a configuration where all transmission power capacity is concentrated on a single route. The findings presented here will be subject to further discussion in Chapter 9, the discussion chapter.

7 Institutional Analysis: Theoretical Background and Method

This chapter will first describe some essential theoretical background on institutions in transmission infrastructure development in subsection 7.1. Then it will determine the scope of the institutional analysis in subsection 7.2. Following the determination of the framework for institutional analysis in subsection 7.3. Finally, describe the methodology for the institutional analysis in subsubsection 7.5.2 of electricity transmission infrastructure development in Indonesia.

7.1 Institutions of transmission infrastructure development

As found in the techno-economical optimization, inter-island interconnections are likely to be necessary to accommodate the transition towards a net-zero emissions energy system in Indonesia. As electricity infrastructure is a socio-technical system, as determined in various relevant publications of the academic world [Kunneke et al., 2021b], it contains both technical complexity, public and private organisations, involves societal actors and has a huge scale [Kunneke et al., 2021b]. The transition towards a electricity infrastructure that can accommodate renewable energy sources does therefore not only involve technological and economic decisions and changes. Existing institutions can be a barrier to the implementation of such a system as the interconnected power system will need combined governance and regulation [O'Connor et al., 2022]. The analysis of institutions helps to identify the factors decision-makers should consider when designing the organisation of transactions in a network infrastructure. [Kunneke et al., 2021a]. However, due to the history of dominating public utilities that controlled the network industries, analysing the institutions was not always necessary. However, now most infrastructure networks have become natural monopolies, organizational choice becomes relevant. Especially for the topic of electricity infrastructure interconnections, institutional transactions must be implemented and coordinated in specific ways, which require choosing organizational solutions accordingly [Kunneke et al., 2021a].

The power system in Indonesia is a complex network involving multiple actors such as transmission operators, policymakers, system designers, consumers, and various institutions and collaborations. To analyze the institutions of the transmission infrastructure development in Indonesia, various approaches are available, including various frameworks to analyze the dynamics of the system, such as the Multi-level perspective (MLP) or Institutional analysis and development framework (IAD Framework) by E. Ostrom [Ostrom, 2005]. The MLP framework focuses on the interplay between niches, regimes, and landscapes. Researchers Verbong and Geels have employed the MLP framework to examine the transition to an interconnected European Supergrid. [Verbong and Geels, 2010]. Another framework that can be used to analyze the opportunities for the stimulation of the transition is analyzing the existing institutions using the four-level framework of Williamson [Williamson, 1998]. It is based on the idea that institutions exist at different levels of a socio-technical system, and that each level has its own set of dynamics and purpose [Williamson, 1998]. While this framework originated from transaction cost economics, it has been applied numerous times for renewable energy issues and complex network topics.

7.1.1 Smart grids or Super grids

The transition to a renewable energy system requires the development of the current energy infrastructure while maintaining sufficient power quality for power consumers [Scholten and Künneke, 2016]. The approach to this development of the electricity grid can be broadly categorized into two sides. One side advocates for improving the existing grid by incorporating smart technologies and decentralized methods to meet the increasing demand (SmartGrid). The other side emphasizes interconnecting all grids and leveraging the strengths of renewable energy sources based on their geographical locations and availability (Super Grid) [Verbong and Geels, 2010]. Importantly, these two perspectives are not mutually exclusive from a technological perspective and can be pursued simultaneously [Verbong and Geels, 2010]. By developing the grid through interconnection and utilizing smarter decentralized assets, the entire system can become more robust and efficient [Blarke and Jenkins, 2013].

However, there are differences between these pathways from a societal perspective. The development of a Super Grid requires relatively low levels of innovation, as most of the necessary technologies, such as long-distance transmission cables, inverters, and transformers, already exist and are in use. On the other hand, the Smart Grid alternative demands radical innovation in technology and software to effectively measure and manage electricity on the grid [Blarke and Jenkins, 2013].

In the context of transition theory, Verbong and Geels have explored different pathways for the development of electricity infrastructure [Verbruggen et al., 2010]. These pathways align with the differentiation between the Super Grid and Smart Grid approaches. The "reconfiguration" pathway by Verbong and Geels involves national and federal policies shaping the transition alongside large utilities and operators. This pathway leans towards a Super Grid approach, as it focuses on upgrading existing infrastructure to maintain the role of large utilities. On the other hand, the "alignment" pathway involves the creation of policies by local, municipal, and smaller national organizations [Verbruggen et al., 2010]. This pathway necessitates the establishment of new organizations, solutions, and technologies, aligning with the Smart Grid approach. Verbong and Geels suggest that the emergence of one of these pathways will be led by different stakeholders [Verbruggen et al., 2010]. Blarke and Jenkins build upon this statement and argue that the development of the Smart Grid approach presents greater challenges due to the need for new technologies, organizations, and solutions, while the Super Grid approach benefits from the availability of existing resources [Blarke and Jenkins, 2013].

7.2 Scope of the institutional analysis

As mentioned in the previous section, the implementation of island interconnections aligns with the "Super Grid" scenario within the grid development approach. Consequently, the societal transition necessitates changes in institutions and collaborations at the national and federal levels, involving large utilities and operators [Blarke and Jenkins, 2013]. Since the inter-island interconnections as described in the techno-economical analysis are not developed yet in Indonesia, this study will analyse the topic of transmission infrastructure development related to inter-island interconnections. This can be interpreted as taking a step back to overall transmission infrastructure development, on which foundations the inter-island interconnections have to be developed.

7.3 Frameworks for analyzing institutions

The implementation of inter-island interconnections might require societal changes and adjustments in institutions and collaborations at the national and federal levels, involving major utilities and operators [Blarke and Jenkins, 2013]. To comprehensively understand and address these institutional changes, various methods and frameworks in institutional studies can be used [Verbruggen et al., 2010, Scholten and Künneke, 2016]. One useful framework is Williamson's four-level approach, which analyzes public-private collaboration in rules, agreements, and contracts with a focus on reducing transaction costs and mitigating opportunism [Williamson, 1998]. The four-level framework of Williamson is selected for this study for the following reasons. This framework has an emphasis on the institutions spread across different levels of the system and is therefore a much-used framework in complex system transition issues. Moreover, as indicated, the framework is often used in connected and similar studies however, not yet for interconnecting Indonesia's electricity system subsection 2.2. Therefore, this study aims to address this knowledge gap by applying an existing and proven framework to a new subject. However, as research describes, the limitations of this framework, relying solely on Williamson may not fully capture the broader social, cultural, historical, and political dimensions influencing the transition [Scholten and Künneke, 2016, Kucharski and Unesaki, 2018a].

To ensure a more holistic analysis, this study will also include a stakeholder analysis to understand diverse perspectives and interests involved in the transition [Andrews-Speed, 2016]. Additionally, examining Indonesia's political history in relation to electricity infrastructure will shed light on the historical context shaping institutional changes [Williamson, 2000]. By integrating these dimensions into the analysis, the research aims to provide more comprehensive insights into the institutional landscape and offer well-rounded design proposals to improve the institutional environment.

7.4 Williamson's four levels

This framework comprises four levels that collectively describe various aspects of the existing institutions. The levels are categorized based on two metrics, whereas the first one considers an indicative frequency of

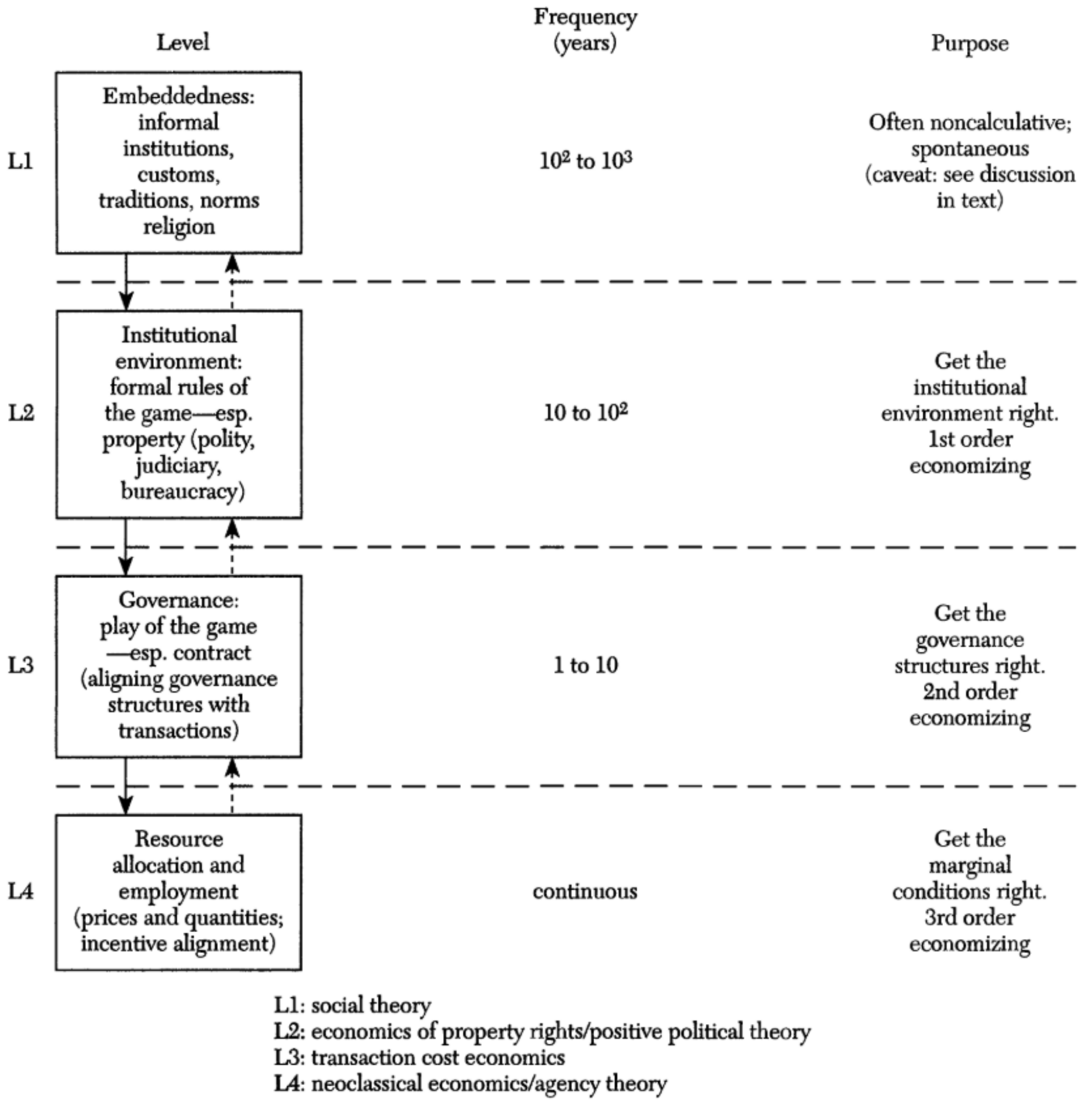


Figure 7.1: Williamson four-levels framework [Williamson, 2000]

change in the institutions, starting at slow-changing institutions and moving to faster-moving institutions. The second metric is the level of effort it takes to change one of the institutions at that level. The first paper in which Williamson introduced the framework was in 1998 [Williamson, 1998]. Then later in 2000, the author revised the framework and described the relevance and most important uses of each level in the framework [Williamson, 2000]. This study will be built upon his most recent work which we are explained more in-depth in subsubsection 7.4.1. The four levels from the Williamson framework are as follows: Level 1) Embeddedness, Level 2) Institutional environment, Level 3) Governance, and Level 4) Resource allocation and employment which can be seen in Figure 7.1.

7.4.1 Levels of the Williamson four-level framework

The first level (L1) of the framework is entitled *'Embeddedness'*. In this level, all institutions are placed that have to do with mostly informal institutions that are rooted in culture, heritage and social norms and habits. These institutions have developed over time and are not necessarily bound to economic reasoning. The institutions at this level are slowly changing, from a century up to even a millennium.

The second level (L2), is called the *'Institutional Environment'* and contains the formal institutions as the state structure, government, property rights, and public bureaucracy are governed by legal rules. These institutions are still quite stable and tend to change every 10 to 100 years.

The third level (L3), named *'Governance'*, contains the actual result of the formal and informal institutions that are established in Levels 1 and 2. It involves specific governance structures such as contracts, firms, or public bureaus to regulate interactions between different actors. These institutions are more dynamic and tend to change every 1 to 10 years.

Lastly, the fourth level *'Resource Allocation'*, contains the institutions that deal with the short-term distribution of goods and services based on the existing governance structure from Level 3. The aim of these institutions is to achieve specific objectives, like maximizing profits, by efficiently allocating resources. These institutions are constantly changing.

As mentioned in subsection 7.4, the revision by the author himself led to the further categorization of the levels as can be seen in the text at the bottom of Figure 7.1. Although all the levels influence each other and build upon each other, different levels can be more relevant for institution analysis depending on its objective. The first level (L1) tends to be more important for social theory, while in economic analysis this level tends to be taken as a given. The next level (L2) tends to be able to be influenced by institutional changes and economics and is therefore very interesting from institutional transformation studies. This can also be stated for the next level (L3), in which the play of the game is guided by governance institutions. Lastly, the fourth level (L4), is mainly related to neoclassical economics or agency theory.

7.4.2 The application of Williamson's framework in the electricity sector

Previous academic studies have explored the application of Williamson's four-level framework to energy infrastructure design. For instance, Scholten et al. (2016) [Scholten and Künneke, 2016] have adapted the four levels of Williamson's framework to align with the existing institutions in energy infrastructure. In this adaption, the emphasis is on the differences and alignment between the technical and economic design of energy infrastructures. The study demonstrates that for each level, the application will look very different for both disciplines, even when applied to exactly the same case. It shows that it is important to consider both pillars of energy infrastructure design in order to perform a comprehensive analysis. Where the alignment of the levels is done with linkage themes 'Access', 'Responsibilities' and 'Coordination'. The insights of this paper are highly relevant for analysing energy infrastructure. The resulting framework of the study can be seen in Figure 7.2 adapted from [Scholten and Künneke, 2016], whereas the left side shows the technical framework, the right side shows the economic and the words in the middle show the linkages.

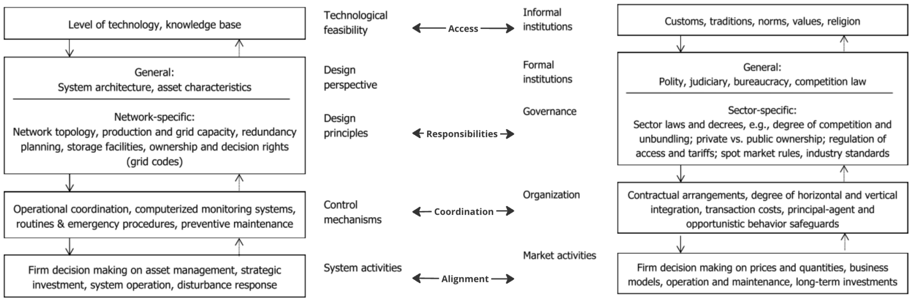


Figure 7.2: Williamson's four-level framework modified for energy infrastructure design [Scholten and Künneke, 2016]

7.5 Institutional analysis methodology

The institutional analysis will start with an overview of the most important stakeholders and their interactions. Then an institutional analysis will be carried out, using the second and third levels of the Williamson four-level framework. Lastly, design proposals will be made to lower the barriers found in the analysis.

7.5.1 Stakeholder Analysis

The stakeholders in the Indonesian electricity sector have been mapped in various studies [Simanjuntak, 2021, Langer et al., 2021, Setyowati and Quist, 2022]. Therefore, the stakeholder analysis in this study will build upon the existing knowledge and add information specific to electricity infrastructure. The stakeholder analysis will start with a description of the stakeholder's activities, objectives and relations with each other. Followed by a figure that summarises the stakeholder's relations towards each other, current regulations and plans. This figure is based on a study done by Sergio Simanjuntak and adapted for the specific case of electricity infrastructure [Simanjuntak, 2021]. The methodology for this analysis is taken from the 'steps in actor analyses' from the book Policy Analysis of Multi-Actor Systems [Enserink et al., 2022]. This method was originally spread over six steps but the limited scope of this study the analysis contains the first four steps. These are:

1. Formulation of a problem and associated decision arena as a point of departure.
2. Identification of the actors involved.
3. Mapping the formal institutional playing field: Chart the formal institutions and relations of actors.
4. Identifying actor characteristics: Determining the interests, objectives, perceptions and resources of actors.

In this study, the most important institutional themes are determined as a first step, these are further described in subsubsection 7.5.2. In the second step, the actors relevant to this problem and decision space are listed. In the third step, the formal institutions relevant to the actors and defined problems are identified and connected to the actors. The last step covers the objectives of the actors. All of the steps are carried out through literature study as desk research. On one hand from currently available regulations and policy documents and on the other hand from descriptive literature on Indonesia's electricity sector [Maulidia et al., 2019, Simanjuntak, 2021, Langer et al., 2021, Setyowati and Quist, 2022, Ordonez et al., 2020].

7.5.2 Institutional Analysis

Based on previous reflections by S. Simanjuntak (2021) and Kucharski & Unesaki (2018) [Kucharski and Unesaki, 2018b, Simanjuntak, 2021], institutional analysis in electricity system transitions are especially interesting in the second and third level of the Williamson framework. The reasoning for this is that the institutions on these levels are most relevant and likely to be influential on the system's transition in the short to middle long term. Therefore, the institutional analysis in this study is focused on these two levels. However, as mentioned by S. Simanjuntak (2021) and Scholten & Künneke (2016), the first level is necessary to understand where the decision-making and level of awareness of the sustainability targets are in Indonesia. Therefore, this study also includes concepts from the first level.

Within these three levels, the focus lies on four critical institutional aspects. These critical institutional aspects are determined from the theoretical background and techno-economic optimization and then tailored to comply with the Williamson-inspired framework by Scholten [Scholten and Künneke, 2016]. From this process, the three most important aspects are determined which will be discussed in the following section.

The first topic is within the informal institutions, considering the level of interconnection technology in Indonesia and the awareness of the necessity of this technology. The second aspect is the planning of transmission infrastructure, as this is the most crucial aspect of the techno-economic analysis. The third aspect is the financing of transmission infrastructure, a factor that significantly shapes the previous techno-economic optimization approach. Worth highlighting is the consistent discussion of energy transition financing across the literature we've reviewed for this study [International Energy Agency, 2020, IESR, 2023]. The last aspect is a result of the two previous aspects since literature showed that contractual agreements are an important aspect of network development [Kunneke et al., 2021c]. Throughout the analysis, it became clear that from transmission development related to interconnections, contracting between public and private parties is needed. Therefore, the last aspect is 'contractual arrangements between public and private parties'. Whereas the first topic is analysed in level 1 (embeddedness) the next two critical transactions are analysed in level 2 (institutional environment). The last transaction is analysed in level 3 (governance).

After the analysis of the institutional setting and identified barriers, the analysis will and with providing design proposals to lower the found barriers. These design proposals will be drawn from statements found in literature, examples of other interconnection projects and interpretations.

7.5.3 Data Collection

The described topics are analysed under the guidance of the Williamson framework in this study. The data used for this analysis is gathered through desk research. This contains the use of literature found in academic sources, industry reports and official regulations. This decision is made because of the wide availability of literature on the topic and the limited timeline of this study. The limitations of this method are that through relying only on desk research, there is a possibility that the study misses out on context that is only available through interviews or surveys [Enserink et al., 2022]. However, because of the limited timeline and scope of this study, validation interviews are used to rely on the expertise of experts to validate the results of this analysis.

7.5.4 Validation

The conclusion of the institutional analysis is an overview of the barriers found in the institutional setting for the development of inter-island interconnections. The analysis ends with proposed institutional design proposals that aim to lower the barriers. The proposed interventions are based on literature and reports. However, since they will influence the system as a whole, more aspects, out of the scope of this analysis will be influenced. Therefore, two semi-structured validation interviews were performed with two professors of Delft University of Technology who have expertise in the institutional side of the electricity system. The interviews are limited to professors from the university due to the limited time of this study. The semi-structured interviews were guided by five questions that were sent in advance to the professors, together with a summary of the institutional analysis. However, the conversation in the interviews flowed to other directions as the professors shared their expertise. The questions and transcript of the two interviews can be found in the Appendix in section 10.3. The outcomes of these interviews are used to validate the proposed design proposals and provide a more holistic perspective on the needed institutional changes.

Professor A. Correljé the first professor who provided validation is an expert on themes concerning the institutional or economic perspective on policies and regulations. He focuses specifically on infrastructure sectors like gas, water and electricity. The second expert interview is with Professor L. de Vries, an expert on the design of the energy sector market and its regulation. Moreover, de Vries is an expert on the integration of energy systems.

This methodology chapter outlines the institutional analysis method employed in this study. It begins with a broad examination of the institutional context, followed by a concise overview of existing institutional analysis frameworks. Subsequently, the chapter elaborates on the rationale behind selecting the Williamson framework. It proceeds to detail the precise methodology for applying the Williamson framework to the study's subject matter, which includes stakeholder analysis, framework application, and result validation. The outcomes of this method will be presented in Chapter 8, the subsequent chapter.

8 Institutional Analysis: Results

This chapter will first describe the results of the stakeholder analysis in subsection 8.1, then describe the results from the institutional analysis, using the Williamson framework applied to electricity transmission infrastructure on level two and level three in subsection 8.3. Lastly, this chapter will share institutional design proposals to the identified institutional barriers in subsection 8.6.

8.1 Stakeholder Analysis

8.1.1 In short

The Indonesian electricity infrastructure sector encompasses various organisations, markets and policies. The sector contains both horizontal and vertical fragmentation in decision-making and influence [Marquardt, 2014]. In short, the dominant operating organization within the sector is PLN (Perusahaan Listrik Negara), which is classified as a "Persero" - a term used to describe Indonesian state-owned business entities primarily owned by the government [Cekindo,]. PLN operates as a stock-based company, aiming to generate profits while providing public services. Its initial capital is derived partially or entirely from state assets in the form of shares. PLN is led by directors, and its employees have private employee status.

PLN holds responsibility for the majority of electricity generation, distribution, transmission, and system operation in Indonesia. However, the company's operations are influenced by policies, strategies, and financial resources from various ministries within Indonesia. The Ministry of Energy and Mineral Resources (ESDM) formulates policies and regulations for the electricity sector. The Ministry of Finance makes decisions regarding subsidies and loans. The Ministry of State-Owned Enterprises serves as a shareholder for PLN, and the National Development Planning Body (BAPPENAS) plays a role in planning Indonesia's overall development. Therefore, PLN cannot act independently but is influenced and directed by other governmental organizations [Marquardt, 2014]. The following section will provide a more in-depth summary of each stakeholder.

8.1.2 National Energy Council

NEC is a national, independent, and permanent body responsible for designing high-level, long-term plans for the energy sector. It is composed of high-level government officials and stakeholder representatives appointed by the President and the Parliament, respectively. NEC's main task is to develop the National Energy Policy (KEN) [Government of Indonesia, 2014b] and set the General Plan for National Energy (RUEN) [Government of Indonesia, 2017]. It also supervises the implementation of energy policies across sectors, with an interest in sustainable energy provision [Simanjuntak, 2021].

8.1.3 Ministry of Energy and Mineral Resources (MEMR)

MEMR is responsible for devising and implementing policies in the energy and electricity sector [Maulidia et al., 2019]. It plays a crucial role in operationalizing KEN into RUEN and the General Plan for National Electricity (RUKN [EDSM, 2019]). MEMR also influences policymaking related to electricity purchase prices and property rights. Two relevant subdivisions are the Directorate General of Electricity (DGE) and the Directorate General of New Renewable Energy and Energy Conservation (DGNREEC) [Setyowati and Quist, 2022].

8.1.4 Ministry of Finance (MF)

MF supports the President on Indonesia in administering the state's finances and provides design proposals for fiscal and monetary policies [Simanjuntak, 2021]. It can create renewable energy incentives through tax policies and financing to lower investment costs. MF also proposes the maximum state budget allocation for the subsidy to PLN, which is crucial for electricity price-setting. Moreover, MF is involved in the contractual arrangements with foreign investments and determines which sectors are allowed to receive those investments [Asian Development Bank, 2020b].

8.1.5 Ministry of State-Owned Enterprises (MSOE)

MSOE assists the President in the governance of state-owned enterprises (SOE), PLN is, as described, one of these SOE's [Maulidia et al., 2019]. The MSOE is authorized to implement policies for sustainable growth and enhanced business performance of SOEs. The MSOE can indirectly influence PLN's transmission infrastructure planning and contracting with power suppliers [Simanjuntak, 2021].

8.1.6 Ministry of Investment

The newly established Ministry of Investment is responsible for implementing existing regulations on investment and policymaking related to investments [Simanjuntak, 2021]. It issues Business Licensing for electricity sector enterprises and plays a role in addressing governance issues surrounding contracts. They are also involved with public-private partnerships and contracting [Asian Development Bank, 2020b].

8.1.7 Regional Governments

Regional governments translate the General Plan of Regional Energy (RUED) into regional plans, which is the General Plan for Regional Electricity (RUKD) [Simanjuntak, 2021]. Moreover, they have a role in the determination of the plans that are presented in the Regional Electricity Supply Business License (RUPTL) of electricity enterprises, mostly PLN [ESDM and PLN, 2021]. Regional governments also devise regional policies and incentives for renewable energy projects and play a crucial role in supporting successful project development [Maulidia et al., 2019].

8.1.8 The Parliament (DPR)

The Parliament is involved in legislation, including the establishment of the regulatory framework for renewable energy. The DPR has the authority to accept or reject legislation, including Government Regulations (GR) that replace Laws [Bridle et al., 2018]. By approving the state budget, the DPR influences the funding available for transmission infrastructure development and other energy-related projects in the country [Ministry of Finance, 2022].

8.1.9 PLN (State-Owned Electricity Company)

As described, PLN is a state-owned enterprise and a monopolist in the electricity transmission and distribution sector. The company is a single buyer for power-generating enterprises (IPPs) and has considerable influence over power plants and PPAs. Moreover, it owns and developed almost all transmission and distribution infrastructure in Indonesia [Asian Development Bank, 2020c]. However, PLN's decision-making is influenced by almost all other stakeholders and is therefore bound to listen to hierarchy [Maulidia et al., 2019].

8.1.10 Stakeholders and institutions visualization

Sergio Simanjuntak conducted an extensive study that resulted in a comprehensive perspective of the stakeholders of the Indonesian electricity sector, of which he created a visual overview. As explained in the methodology, for this study, that figure is analyzed and complemented with information relevant to the electricity infrastructure in Indonesia. The visualization can be found in Figure 8.1, to visually explain the dynamics between actors.

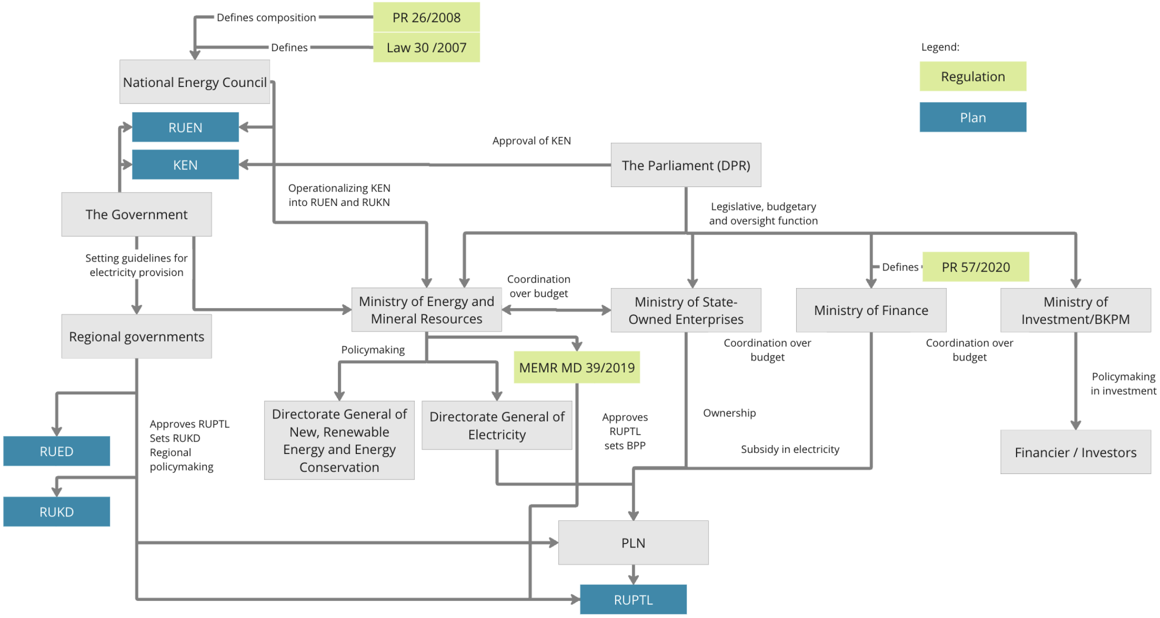


Figure 8.1: Overview Indonesian electricity sector stakeholders relevant to infrastructure, based on [Simanjuntak, 2021]

8.2 Institutional Analysis under level 1: Embeddedness

In this section, the institutional embeddedness for the implementation of inter-island electricity infrastructure in Indonesia is analysed, based on the concepts from Scholten & Kunneke (2016). The section starts with a sketch of the institutional foundations in Indonesia. Then, on one hand, the existing level of technology knowledge will be discussed. On the other hand, the found convictions concerning inter-island interconnection will be presented. The section is organized as follows, first, the current institutions in place are identified. Then, the identified barriers are described. Finally, the potential solutions to these barriers, as found in the literature, are described.

8.2.1 Embeddedness - Current Institutions

As described, Indonesia's unique geography and context are marked by a diverse mixture of social, cultural, and institutional elements, all of which exert a strong influence on how infrastructure projects are conceived, negotiated, and executed [WorldBank, 2023]. Moreover, although the embedded institutions are known to change rather slowly, Indonesia has been going through significant institutional changes while focusing on electricity system developments [WorldBank, 2023].

The foundation of the organisational principles of Indonesia is established in the 1945 Constitution of the Republic of Indonesia [Government of Indonesia, 1945]. In this document, the organisation and hierarchies of Indonesia's regulations are determined. The following Figure 8.2 shows an overview of this hierarchy, adapted from [Simanjuntak, 2021]. From this hierarchy, two overarching laws are crucial for any development in the energy sector these are the Energy Law PR 30/2007 [Government of Indonesia, 2007] and the Electricity Law PR 30/2009 [Government of Indonesia, 2009].

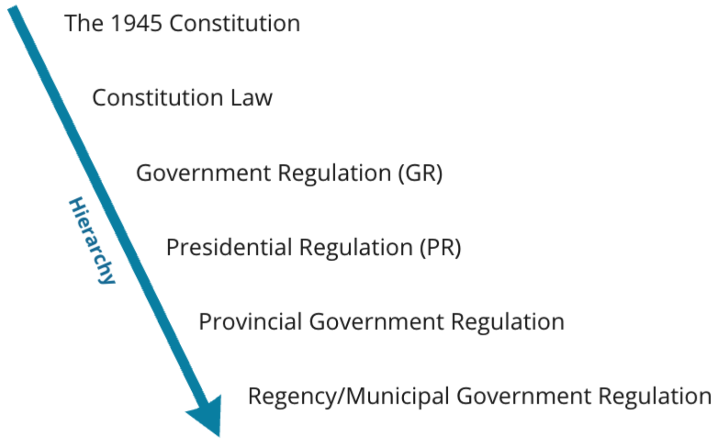


Figure 8.2: Overview of the hierarchy of Indonesian regulations, adapted from [Simanjuntak, 2021]

As described in subsection 8.1, PLN is the main operator of Indonesia's electricity system. From a historical standpoint, when Indonesia became independent again after World War II, the Indonesian government became the operator of all electricity assets [PT PLN (Persero),]. After two decades, PLN was established in 1961, as the electricity service supplier of Indonesia [PT PLN (Persero),]. From this moment, PLN has been a government-owned monopolist, creating opportunities for private investment from 1994 onward [PT PLN (Persero),]. In terms of existing technological knowledge, PLN has managed to build almost the entire electricity system that covers Indonesia to this date. This system also contains one submarine HVDC interconnection link, between Java and Bali [ESDM and PLN, 2021]. Moreover, PLN is expanding their technology knowledge with electricity system-related partnerships with Huawei and energy software developer Energy Exemplar [Theron-Ord, 2023, Team Energy Exemplar, 2023].

Next to the technological perspective, there has also been a shift in how the development of the electricity system in general in Indonesia is perceived by its inhabitants and institutions. Indonesia is one of the biggest coal exporters in the world [IEA,]. This industry provides great economic wealth and growth

[Sembiring, 2022]. However, this does not comply with the rising awareness of climate change that has been a global transition. In Indonesia, a significant shift has been the announcement of the net-zero 2060 target by President Joko Widodo on the COP27 [IEA,]. This influences electricity infrastructure development since the Indonesian electricity sector is strongly intertwined with politics. As can be seen in subsection 8.1, all the stakeholders are positioned under government organisations. The system operator PLN is a state-owned company which therefore automatically creates a dimension of political influence. The results of this can be seen in the most recent RUPTL, in which the plan includes more renewable power plants than fossil power plants for the first time [IESR, 2023, ESDM and PLN, 2021].

However, there are indications that the awareness and willingness to change to a new energy system, specifically an interconnected energy system, are somewhat blocked. An example of this is the outcomes of interviews conducted by the researchers Ordonez and Eckstein. Their study states that discussions in Indonesia centre on challenges associated with integrating renewable energy sources into the power system, particularly due to their variability. These discussions underscore concerns regarding grid stability, and inflexible grid management however, establishing interconnections between the islands is seen as too complex and not feasible [Ordonez et al., 2020]. Moreover, a report from the Technological University of Singapore (2022), states that there are numerous challenges to the net-zero 2060 ambition that have to do with the lack of public trust and sustainability vision [Sembiring, 2022].

8.3 Institutional Analysis under level 2: Institutional Environment

In this section, the institutional environment for the implementation of inter-island electricity infrastructure in Indonesia is analysed. The analysis is scoped into two most relevant determined aspects, the capacity planning for infrastructure and the institutions in place for financing the infrastructure. As the scope of this study focuses on inter-island interconnection from a systems perspective, only the national plans and laws will be included. Since the inter-island interconnections always include multiple regions. The section is organized as follows, first, the current institutions in place are identified. Then, the identified barriers are described. Finally, the potential solutions to these barriers, as found in the literature, are described.

8.3.1 Transmission Capacity Planning - Current Institutions

As described in subsection 8.1, the planning of the electricity network is steered through a hierarchical process and eventually carried out by the organization PLN. Under its Persero rights for conducting electricity business in Indonesia, PLN retains sole ownership of transmission and distribution assets in the country. Independent Power Producers (IPPs) may construct transmission or distribution lines, but ownership is usually transferred to PLN upon completion [ESDM and PLN, 2021].

In Indonesia, it is obligated by law that the title of 'Izin Usaha Penyediaan Tenaga Listrik untuk Kepentingan Umum' (IUPTLU), is a requirement to be involved in the Indonesian electricity transmission business. The IUPTLU holders are holders of power supply business licence for public interest [Cekindo,]. In exercising their function to supply electricity for public purposes, IUPTLU holders have rights to cross rivers, lakes, seas, streets and railroads, above or under buildings, gas pipes and infrastructure as well as forest areas. The IUPTL is a necessary title to be involved in the Indonesian transmission business following GR 14/2012 [Government of Indonesia, 2012]. PLN is the biggest IUPTLU holder in Indonesia.

Since PLN is a Persero, it is instructed through the state and the governmental plans higher up the hierarchy. The organisation of this hierarchy is determined in the energy regulation GR 30/2007 [Government of Indonesia, 2007]. Starting at the top of the hierarchy, the long-term plan for the energy system as a whole is created by the National Energy Council (DEC). This council consists of various high-ranking officials and stakeholders appointed by the president and the parliament. The DEC creates the National Energy Policy Plan (KEN) [Government of Indonesia, 2014b] and the General Plan for National Energy (RUEN) [Setyowati and Quist, 2022]. Related to electricity infrastructure planning, these plans determine the overall strategy of the system as a whole. Whereas relevant to transmission grid planning, the most recent RUEN states that the current electricity infrastructure in Indonesia is not sufficient and there are multiple strategic solutions proposed on how to improve infrastructure. Among others, these solutions consist of developing new infrastructure projects and building more interconnection within islands [Government of Indonesia, 2017]. The most important result of the KEN is the target of net zero in 2060 and the aim of implementing renewable technologies in the

Indonesian grid. As described, the implementation of renewable technologies requires the implementation of the expansion of the transmission infrastructure [Abujarad et al., 2017]. However, these two plans are the basis of the development and set the targets, they do not contain a specific plan on implementation of how to reach those targets. This is where the RUED comes into place, this is a plan that exists for every region in Indonesia on the plans for energy development. This also draws a concrete line to the national plan for electricity, the RUKN. On the other hand, the RUKN is influenced by the plans and regulations for electricity developments. The organizational structure for electricity plans is determined in the electricity regulation GR 30/2009 [Government of Indonesia, 2009]. The RUKN is the national plan of electricity that is then adapted to a regional plan for electricity (RUKD), for every region in Indonesia. The last plan that brings all the above plans together and actually provides the projects planned for the expansion of electricity-related structure is the yearly plan from PLN, the RUPTL [ESDM and PLN, 2021]. The organisation of these plans are visualized in the following Figure 8.3.

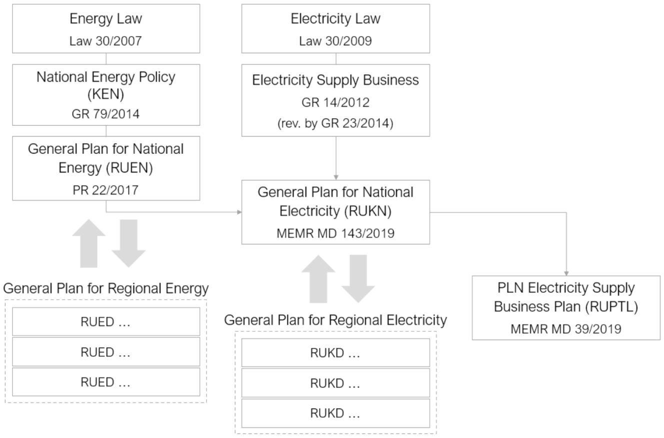


Figure 8.3: Overview of influences of infrastructure plans, adapted from [Simanjuntak, 2021]

The process for planning electricity infrastructure by PLN is described in the RUPTL and based on analysis and feasibility studies. The process of planning starts with the load forecast, moving into the generation expansion function, and then the capacity adequacy is determined, which is an iterative process with transmission expansion, network quality & reliability assessment and production simulation. These steps eventually lead to the planning decision, which is visualised in the following Figure 8.4.

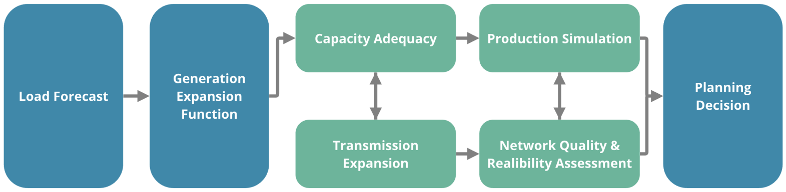


Figure 8.4: Process PLN adapted from [FCDO, 2022]

The RUPTL contains the planned electricity structure planning for the coming ten years and is updated every year. Thus, the most recent variant of the RUPTL to this date is the planning from 2022 to 2032. Following this law, the Electricity Supply Businesses also co-create the RUKN under the regulation GR 23/2014 [Government of Indonesia, 2014a], set by EDSM.

As for the relevance to transmission infrastructure development, the most recent RUKN states the following points [EDSM, 2019]. The recent RUKN places significant emphasis on transmission infrastructure development. This includes the establishment of High-Voltage Direct Current (HVDC) networks, which play a crucial role in ensuring efficient and reliable electricity transmission. Moreover, a key objective outlined in the RUKN involves the integration of the Sumatra and Java-Bali systems through an HVDC transmission network. Furthermore, the RUKN highlights efforts geared towards enhancing the overall reliability of the grid. This entails directing electricity towards special economic zones, tourism centres, and industrial hubs. In the face of projected annual electricity demand growth of 6.9%, particularly driven by industrial sector consumption, the RUKN acknowledges the imperative for enhanced infrastructure. This underscores the need for continuous expansion and improvement of the electricity transmission network to accommodate the evolving demands of various sectors [EDSM, 2019]. Overall, the RUKN's comprehensive approach to transmission infrastructure planning underscores its commitment to building a robust, interconnected, and sustainable electricity grid for Indonesia's future.

ESDM, the governing organisation above PLN, as described, released their strategic outlook for 2020 - 2024, in this outlook some key points relevant to inter-island transmission infrastructure were mentioned [ESDM, 2020b]. First, the plan stresses the importance of providing a consistent electricity supply to bolster regional economic growth and facilitate the expansion of industries. Equally significant is ESDM's commitment to ensuring a reliable electricity supply that adequately supports the establishment of smelters, whether existing or planned. Moreover, ESDM directs its attention towards PT PLN (Persero) with a call for investment in transmission networks, substations, and dependable distribution systems. The emphasis here extends to the initiation and execution of inter-island transmission projects, which are marked as a pivotal priority. This emphasis on inter-island transmission projects is of particular importance and stands out significantly. It signifies ESDM's resolute focus on fortifying and expanding the transmission infrastructure between the islands, highlighting the strategic significance of such developments in Indonesia's energy landscape [ESDM, 2020b].

This plan also includes the planned electricity infrastructure expansion. As described, inter-island interconnection is part of the electricity infrastructure and plans towards that concept should be included in the RUPTL if planned [Suharsono and Lontoh, 2022]. The following section described the relevant plans from the most recent RUPTL that are planned for infrastructure expansion [ESDM and PLN, 2021].

As described, the RUPTL, which stands for Rencana Usaha Penyediaan Tenaga Listrik (Electricity Supply Business Plan), serves as a comprehensive guideline document for the development of power systems in Indonesia [ESDM and PLN, 2021]. It is jointly created by PLN and the Ministry of Energy and Resources and outlines the strategic roadmap for the next ten years, specifically from the present until 2030. The RUPTL is designed to achieve specific goals and is based on existing policies and criteria that govern the electricity sector in the country [ESDM and PLN, 2021]. However, a report from the Asian Development Bank stated that the planned projects are often not implemented as described in the RUPTL [Asian Development Bank, 2020a].

The RUPTL documents plans for the implementation of various new transmission cables within the 13 regional power systems within Indonesia. The regions under PLN's jurisdiction are divided into Sumatra, Java Madura and Bali, Kalimantan, Sulawesi, Maluku, Papua, and Nusa Tenggara. PLN operates through regional PLN management businesses within these main regions (Figure 8.5).

Figure 8.5: PLN Businesses area map [ESDM and PLN, 2021]

The planning for transmission infrastructure is described in detail in the RUPTL however, these transmission cables are primarily intended for connecting different regions within the same island. For instance, in the Sumatra System, where energy resources such as coal, geothermal, and gas are abundant in South Sumatra, the plan is to transfer the energy to North Sumatra through a high-voltage transmission system

[ESDM and PLN, 2021]. In the most recent RUPTL, there is no plan for inter-island transmission planning.

However, the plan does mention reasons why interconnections between islands are not present as a plan:

> "In general, the selection of power plant locations aims to comply with the principle of regional balance, which means fulfilling the electricity needs of a region mostly through generators located within that region, minimizing dependence on power transfer from other regions through transmission interconnections. By adhering to this principle, the need for interconnection between regions will be minimal." [ESDM and PLN, 2021]

This statement suggests that PLN prioritizes regional balance rather than utilizing all regions to balance the power system as a whole.

However, the RUPTL does discuss options for private-sector investment in transmission system development, including interconnections between islands. The document acknowledges the government's goal of accelerated development of transmission infrastructure for interconnections between electricity systems and, specifically, interconnections between islands in line with government programs and policies.

The transmission projects are typically carried out by PLN, except in cases involving transmission from an Independent Power Plant (IPP). In such instances, the IPP developer is responsible for the transmission project using a Request for Proposal (RFP) document. Additionally, the private sector has the opportunity to undertake transmission projects through schemes like Build Operate Transfer (BOT) or Build Lease Transfer (BLT), in which PLN operates the system during a specified timeframe before transferring it. The transmission assets will be transferred to PLN upon the expiration of the lease period [ESDM and PLN, 2021]. The operation and maintenance of transmission projects carried out under BOT and BLT schemes will be entrusted to PLN, following dispatch orders from the transmission system operator (TSO).

The RUPTL itself does not contain the actual planning of one new inter-island interconnection. This is contradictory to the key objectives written by the Ministry of ESDM in their strategic plan [ESDM, 2020b].

Several regulations play a significant role in shaping transmission capacity planning alongside the existing plans. PR No.77/2008 [President of Indonesia, 2008], issued by the President, outlines the understanding and agreement surrounding the ASEAN Power Grid. Through this document, Indonesia joins other Asian countries in acknowledging the importance of interconnections between nations, even extending to international transmission. This presidential regulation underscores the commitment to submarine grid expansion.

In terms of infrastructure planning, Regulation ESDM 13/2021 [ESDM, 2021] holds relevance as it governs the utilization of land for electricity transmission networks, with a focus on terrestrial rather than maritime environments. Furthermore, individual electricity grids are subject to specific regulations emphasizing the provision of safe and reliable systems. Notably, regulations such as regulation ESDM 37/2008 [ESDM, 2008] and regulation ESDM 20/2020 [ESDM, 2020a] contribute to maintaining the operational integrity of these grids. Regulation ESDM 10/2022 [ESDM, 2022] holds a crucial role by granting private investors or parties access to existing transmission lines within Indonesia's infrastructure. Additionally, a limited number of transmission infrastructure projects, executed by third Independent Power Producers (IPPs), have emerged to link remote IPPs to PLN substations, as highlighted by the Asian Development Bank. Lastly, it is worth noting that Regulation 4/2016 is called 'accelerating electricity infrastructure development' but is oriented towards expediting the development of electricity generation plants, rather than focusing on transmission infrastructure [President of Indonesia, 2016a].

8.3.2 Transmission Capacity Planning - Institutional barriers

Through the literature analysis on the current institutions on transmission capacity planning in Indonesia and the examination of national plans, barriers are identified. The following section describes the two main findings on barriers, first of all, the lack of inter-island transmission planning and second the lack of institutions in place to guide the planning of submarine and inter-island transmission capacity.

As described, the planning of transmission capacity is currently determined through a hierarchical process, strategically planned through national plans and concretized in PLN's RUPTL. The biggest barrier found in the analysis is the lack of plans in this concretized RUPTL for inter-island interconnections [ESDM and PLN, 2021]. The plans that influence and guide the RUPTL, the RUKN and ESDM's strategic document mention that the interconnections are necessary and should be prioritized [EDSM, 2019, ESDM, 2020b]. However, in the plan up until 2030, the HVDC cables are not found. As mentioned by Ordonez and Eckstein [Ordonez et al., 2020], while the current official documents represent a step in the right direction, the overall energy strategy is primarily driven by political agendas rather than cost-effective planning. Moreover, the Asian World Bank also confirms that the existing plans are not well aligned with each other [Asian Development Bank, 2020a]. The institute IISD concludes that there is a lack of methodology for transmission grid planning in Indonesia as the focus lies more on generation planning [Suharsono et al., 2019]. Moreover, the IESR states in their outlook that the current plans for transmission expansion are not enough to integrate the planned renewable technologies [IESR, 2023]. Considering the goal of achieving net-zero emissions by 2060, there remains a 30-year window to implement both the necessary infrastructure and renewable energy technologies (RET) required to meet this target. Since the development of submarine power cables can take several years, it is crucial to start considering plans and actions soon. The IESR also states that in their modelling, the inter-island interconnections between Java and Kalimantan and between Java and Nusa Tenggara are highly necessary. Following their analysis, the construction of these HVDC interconnections should be started as soon as 2025 [IESR, 2023]. However, there are no project plans in the RUPTL to implement these transmission capacities.

An additional challenge stems from the absence of well-defined regulations governing the planning and safety aspects of underwater transmission infrastructure. While regulations addressing construction and post-construction safety on land exist under regulation ESDM 13/2021, a corresponding framework for sea-based construction and safety is conspicuously absent [ESDM, 2021]. This is particularly relevant when considering the unique geographical factors influencing submarine transmission network planning, as emphasized in section 5 [ESDM, 2021]. Moreover, although regulations and grid codes regulate major individual transmission systems in Indonesia, a gap persists in establishing institutions to facilitate the interconnection of these grids and the harmonization of grid codes. The alignment of these codes and regulations is crucial in streamlining effective interconnected transmission planning [IESR, 2023].

8.3.3 Financing of sufficient transmission capacity - Current Institutions

As described, the development and planning of the transmission infrastructure in the Indonesian power system have so far been solely the responsibility of PLN. In terms of the financing of the planned transmission capacity, the majority of network investments are funded by PLN, while supported by funds from Development Financial Institutions (DFIs) and Export Credit Agencies (ECAs). The same report created by the IEA shows that about one-third of investment in the Indonesian power sector has been used for power networks, both distribution and transmission [International Energy Agency, 2020]. One of the legal responsibilities of PLN is to provide secure and reliable electricity to the inhabitants of the archipelago. Various sources indicate that the combination of these responsibilities is unachievable from a financial point of view. Whereas the implementation of renewable technologies requires the expensive expansion of the transmission infrastructure, the income through electricity sales from PLN is not enough to even cover the costs of supply [Asian Development Bank, 2020c]. The EDSM and government provide PLN with subsidies but reports indicate that private investment is necessary to achieve the new infrastructure. Since early 2016, the government of Indonesia has introduced the opportunity for private investment in the transmission network [President of Indonesia, 2016a]. However, due to the historical monopoly, only a small percentage of the current transmission infrastructure is financed by private parties. The following section will discuss the current institutions in place that can serve as a base for financing transmission infrastructure in Indonesia.

First of all, PLN uses part of their income from energy sales and governmental financial resources for the expansion of transmission infrastructure [International Energy Agency, 2020]. Whereas, the income of PLN is about 15% from governmental subsidies and the latter from their revenues as can be seen in Figure 8.6. PLN company reports show that between 2015 and 2018, there was a steep increase in the company's investment in transmission infrastructure. However, this trend flattened in 2018 and the investments were mostly used for electrification targets [Asian Development Bank, 2020a].

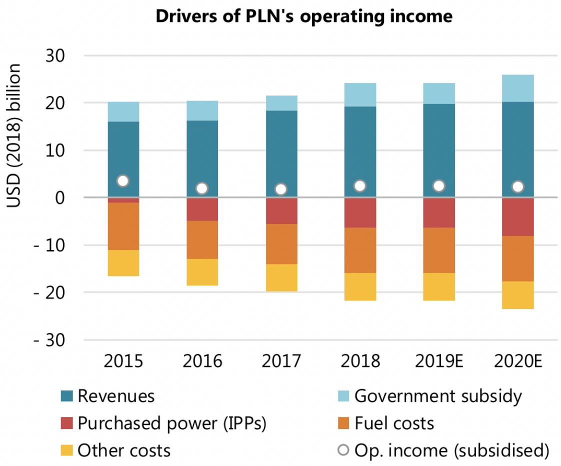


Figure 8.6: Overview of income of PLN, adapted from [International Energy Agency, 2020]

The second set of institutions in place relevant to financing transmission infrastructure is private investment. There are opportunities for private investors to develop transmission infrastructure. This is legalized under the so-called 'foreign investment list' for investment (PR 44/2016) [President of Indonesia, 2016b]. This list shows the percentage of the whole cost of the project that may be financed by investors. For the category 'Transmisi Tenga Listrik' which means 'Electrical Power Transmission', the maximum foreign investment is set to a maximum of 95 percent [Asian Development Bank, 2020b]. However, up until now, no purely private investments have been made in transmission infrastructure [Asian Development Bank, 2020b].

Business Activity	Maximum % of FDI Allowed
Power generation	100%
Power transmission	100%
Power distribution	100%
Oil and gas	75%

FDI = foreign direct investment.

Source: Government of Indonesia. Presidential Regulation No. 44 of 2016 on Lists of Fields That Are closed to and Business Fields That Are Open with Conditions to Investment.

Figure 8.7: Foreign investment allowance in Indonesia, adopted from [Asian Development Bank, 2020b]

The last option for transmission capacity financing is through public financing [Asian Development Bank, 2020b]. Indonesia is involved in public funds and financing schemes that are meant to realise or accelerate the transition towards renewable energy targets in Indonesia. For instance, the Just Energy Transition Partnership (JEPT), includes a big fund that might be used for the development of infrastructure [PT PLN, 2022]. Moreover, the Climate Investment Fund (CIF), is a big fund that Indonesia secured to help phase out fossil power generators [Climate Investment Fund, 2020]. Lastly, the Asian Development Bank (ADB), has approved a million-dollar loan to PLN with the objective of developing better energy infrastructure and renewable energy technologies [Asian Development Bank, 2022]. A historical example of a public loan like this approximately 1.20 billion dollar loan by various financing institutions in 2017 to develop electricity infrastructure [The Jakarta Post, 2017].

As described in the previous subsubsection 8.3.1, The Build Operate Transfer (BOT) or Build Lease Transfer (BLT) schemes, are still applicable for private transmission infrastructure investment. Whereas for the development of renewable energy technologies, these schemes are revoked under regulation MEMR 4/2020, with the objective to make the development of renewable energy technologies easier [MEMR, 2020].

A regulation related to the financing of electricity infrastructure is regulation ESDM 26/2012, which describes the procedure for sales, purchase and permits for the interconnection of cross-country electric power networks [ESDM, 2012]. This regulation specifies under which circumstances electricity transactions can be performed between Indonesia and other countries and how the tariffs can be determined. However, this regulation is focused on international interconnection, not national interconnection and does not specify which regulations are in place for the transactions of inter-island interconnections.

8.3.4 Financing of sufficient transmission capacity - Institutional barriers

As identified in the literature analysis, both PLN, reports and academia conclude that PLN does not currently have the financial resources to solely construct an inter-island interconnection transmission network. Therefore, alternative financing structures seem to be necessary. In this section, the identified institutional barriers to transmission capacity expansion are described. Whereas, the first barrier is the lack of institutional structure for investment specifically in transmission infrastructure. Secondly, the lack of attractiveness of existing financing opportunities, which are partly rooted in the high price / low return on investment of transmission network developments in Indonesia [Asian Development Bank, 2020a].

Researcher Maulidia states that the Indonesian government, including PLN, lacks the financial capacity to develop the necessary electricity infrastructure to meet energy transition targets, necessitating private investment [Maulidia et al., 2019]. As Maulidida concludes, PLN will need innovative financing schemes and private-sector investment to be able to implement an interconnected system. The IEA identified that the current burden on the public finances from PLN is a barrier to the development of the transmission infrastructure [International Energy Agency, 2020]. However, there are no specific financing regulations in place that could be used as a foundation for foreign investment in the Indonesian transmission grid development [Asian Development Bank, 2020b]. Investment in transmission and distribution is often connected to increasing the electrification rate, not so much to increasing power system balance and stability [International Energy Agency, 2020]. This is partly caused by the lack of communication on the importance of improved transmission infrastructure, as stated by the ADB [Asian Development Bank, 2020a]. Moreover, the historical monopolistic nature of transmission grid development in Indonesia by PLN causes the alternative financing options are not yet much exploited. The IEA found that at the moment, PLN does not attract enough capital from alternative investors [International Energy Agency, 2020].

The second barrier is about the lack of attractiveness of the existing financing opportunities. One key issue pertains to power purchase prices, which are currently set at levels that are insufficient for developers to recuperate their investments and achieve reasonable profits. This concern has been exacerbated by the implementation of Regulations PR 12/2017 and PR 50/2017, which cap power purchase prices at 85 percent of the local average generation cost (BPP) [President of Indonesia, 2017a, President of Indonesia, 2017b]. These regulations, as noted in the report by Bridle et al., have intensified the financial difficulties faced by developers seeking to establish renewable energy projects [Bridle et al., 2018]. The ADB echos this statement, saying that current electricity tarrifs are not even able to return the cost of investment in the current operations of PLN, which causes dependence on subsidies and overall government finances [Asian Development Bank, 2020a]. This is partly caused by the low electricity tariff determined by the government makes investment in this sector unattractive. [Maulidia et al., 2019]. Moreover, investment will always come with risks but the risks found in reports related to investment in the Indonesian power sector are found to also be related to the uncertainty of payment and PLN's history of renegotiating previous projects to policy risks related to difficulties with permits and the dynamic regulatory landscape [International Energy Agency, 2020]. This is in line with a report from the Asian Development Bank, stating that private investment is difficult due to uncertainties in the business and political environment. [Asian Development Bank, 2020a]. Moreover, the landscape is further complicated by the volatility introduced through frequent policy alterations and regulatory delays. The government-owned utility, PLN, has also demonstrated inconsistent adherence to government policies, thereby eroding investor confidence and heightening the risk associated with project development [Bridle et al., 2018].

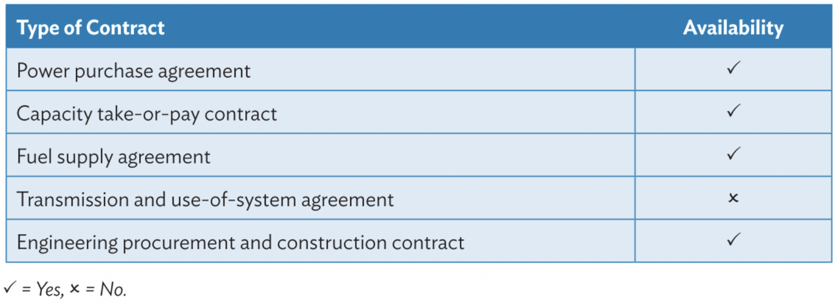
A notable concern from the report from Bridle is the lack of acknowledgement of the environmental advantages of renewable energy within the new pricing framework. In fact, Bridle states in his report that this new system seems to favour conventional fossil fuel sources [Bridle et al., 2018]. The Indonesian government's support and financial backing of the coal industry have artificially lowered the average generation cost of electricity. This linkage between renewable energy prices and coal-generated prices through the BPP has resulted in a scenario where unsubsidized renewables find themselves in competition with subsidized coal generation, placing renewable projects at a comparative disadvantage [Bridle et al., 2018]. As the inter-island transmission network will be used to accommodate renewable sources, the subsidy on coal also worsens the position for investment in the inter-island transmission capacity.

8.4 Institutional Analysis under level 3: Governance

As described in the previous sections, in order to develop the necessary inter-island interconnections, private and foreign financing structures are necessary. This requirement will be taken to the level of governance in this section. This section will discuss the current institutional setting and the identified dilemmas are presented focused on the contractual arrangements between public and private parties of an interconnected transmission system in Indonesia.

8.4.1 Contractual arrangements between public and private parties - Current Institutions

As mentioned in subsection 7.1, the socio-technical system of transmission infrastructure is a complex system. The necessity of alternative investment, next to budgeting from PLN, is an important aspect of the potential implementation of such a system. Whereas, the opportunities and formal institutions are currently opening the door for these alternative investment forms. The governance of these financing structures is an important aspect [Scholten and Künneke, 2016]. However, the literature search found that currently, no specific standardized contract structures are in place to govern contractual agreements between public and private parties for transmission grid development in Indonesia. The reality is that there is a PPP standardization for each identified aspect within the energy sector except for transmission (and distribution) capacity, as can be seen in Figure 8.8.



Type of Contract	Availability
Power purchase agreement	✓
Capacity take-or-pay contract	✓
Fuel supply agreement	✓
Transmission and use-of-system agreement	×
Engineering procurement and construction contract	✓

✓ = Yes, × = No.

Figure 8.8: Availability of standard Public-Private Partnership Contracts in the Energy Sector, adopted from [Asian Development Bank, 2020b]

As can be seen in the figure, there are a few standard contracts in the country for, among others, Power Purchase Agreements (PPA's) and other Public Private Partnerships (PPP) [Asian Development Bank, 2020b]. On these existing contracts, various historical and planned projects have been listed as for example a household gas pipeline system and street lightning in Surakarta [Asian Development Bank, 2020b]. From the existing PPP projects in the energy sector, the biggest part has been procured through unsolicited bids. The other procurement options are 'direct appointment', 'competitive bids' and 'license scheme', which are all used way less.

According to an ADB report, there are intentions to involve private entities in the transmission infrastructure development; however, the exact mechanisms, such as build-lease-transfer or power-wheeling, remain uncertain [Asian Development Bank, 2020b]. It's worth noting that Regulation ESDM 26/2012 delineates the procurement and contractual stipulations for connecting the Indonesian power system with other countries, although these provisions are not yet defined for inter-island interconnections [ESDM, 2012]. Additionally, the regulatory landscape encompasses directives governing transmission grids across distinct power systems. These guidelines contain the grid codes. Whereas historically, all power systems had their own regulation for the grid code (Regulation ESDM 2/2015 for the Sulawesi power grid, ESDM 18/2006 for the Kalimantan power grid, and ESDM 20/2015 for the Java-Madura-Bali power grid), the grid code is now consolidated into one regulation ESDM 20/2020 [ESDM, 2020a]. The grid code is governed by the Management Committee comprising government representatives, PT PLN (Persero), P3B, PT Indonesia Power, regional PT PTL offices, and IPP representatives, these codes undergo periodic development and evaluation. The primary objective of the Aturan Jaringan (Grid Management Code) within the electricity transmission network, as outlined in these regulations, is to ensure the dependable and balance transmission of electricity. This code serves various objectives, including the maintenance of frequency within the balanced range which is 50 Hertz + 0.2 Hertz.

8.4.2 Contractual arrangements between public and private parties - Institutional barriers

The biggest identified barrier is the lack of institutional structures to support the contractual arrangements between public and private parties in transmission grid expansion. Related to this is the barrier of unclarity on upcoming regulations.

In a report from the Asian Development Bank, it is proposed that the way transmission development is structured at this moment is lacking and not capable of recommending transparent tariffs, review and guide investment, among this private investment and SOE investment [Asian Development Bank, 2020a]. Moreover, unstable policies and regulations, make it difficult to have agreements and contracts between public and private parties. This also decreases the trust in the firmness of existing contractual agreements [Asian Development Bank, 2020a]. The unclarity and lack of alignment between the different governing organisations is also a found barrier in the study of Sambodo et al. [Sambodo et al., 2022].

As for the energy sector aspects that do have standard contracts, due to the absence of long-term experience of PLN and private financing, there remains a challenge for the implementation of projects that do get the PPP scheme financing [Asian Development Bank, 2020b]. Moreover, the ADB shared that PLN's approach to power purchase agreements (PPAs) has changed. Previously, PLN offered "take-or-pay" commitments covering the entire PPA duration, ensuring electricity purchase or payment. Now, PLN aligns commitments with senior loan tenure, meaning they commit to purchase or pay for electricity only during the senior loan period. This shift affects developers by increasing revenue risk. Past full-term commitments provided predictable revenue, whereas now, alignment with senior loan duration introduces revenue uncertainty if projects extend beyond that period [Asian Development Bank, 2020b]. These kinds of contractual changes can make investment less attractive and might be relevant for upcoming transmission capacity contracts [Sambodo et al., 2022].

The last barrier worth noting is the lack of regulations concerning the contractual agreements needed to implement interconnection between two power systems. The to-be-developed inter-island interconnections will need to comply with requirements and be closely watched by a governing body to ensure successful implementation [International Energy Agency, 2020a].

8.5 Summary institutional barriers

The following section delineates the outcomes of the institutional analysis conducted in this study concerning existing institutions and the barriers they present. This section offers a short overview of the specific institutional barriers identified for each researched aspect.

In the context of the Williamson framework's second level, which entails the analysis of transmission capacity planning and financing, the literature review detailed in Section subsubsection 8.3.2 reveals that the absence of comprehensive plans for inter-island interconnection within the RUPTL (Electricity Supply Business Plan) constitutes a significant barrier. Additionally, the deficiency of guiding institutions for this planning process compounds the challenge. As for the financing aspect of transmission capacity, as described in section subsubsection 8.3.4, it becomes apparent that there is a lack of viable financial structures capable of funding the requisite transmission infrastructure needed to meet renewable energy targets. Furthermore, the existing structures lack appeal for foreign investment.

In the analysis third level of the Williamson framework, where contractual arrangements between public and private entities are scrutinized (section subsubsection 8.4.2), it becomes evident that the most significant barrier is the absence of institutional frameworks that facilitate these arrangements. It is also noteworthy that there is an element of uncertainty surrounding upcoming regulations on this subject.

8.6 Design proposals for institutional changes and additions

The previous institutional analysis identifies the institutional setting of three very important aspects of the development of inter-island interconnections. From this analysis, three themes for design proposals can be drawn with the objective to improve the institutional landscape of the interconnections. This section will describe the design proposals.

8.6.1 Integrated Transmission Capacity Planning Approach

As described in the institutional analysis, transmission capacity planning is currently influenced by national plans but determined through a technical calculation starting with the load forecast. The long-term importance of inter-island interconnections has been acknowledged in various national plans and reports, but it has not been incorporated into plans in the operational plan, the RUPTL [ESDM and PLN, 2021]. This study agrees with the Institute for Essential Services Reform (IESR), and suggests that the development of inter-island interconnections should begin by 2025 [IESR, 2023]. It is recommended that the development of interconnections be prioritized in all national plans, including the RUPTL. An integrated planning approach is advised, emphasizing the necessity of interconnections for achieving Indonesia's renewable energy goals, as mentioned by the International Energy Agency (IEA) in their report on enhancing the Indonesian power system, and integrating this in the more technical RUPTL.

As the power system analysis of this study shows, inter-island interconnections are a strategic solution for the long-term safety and reliability of the Indonesian power system. As the integration of renewable sources is currently underway, the problems arising from the lack of inter-island interconnections will become apparent in the coming years [International Energy Agency, 2020c]. Considering the timeline in which the lack of inter-island interconnections becomes an issue, it is uncertain whether the RUPTL will address the necessity in time. This study analyzed the Indonesian power system in 2050, while the RUPTL only looks ten years ahead.

With this in mind and the knowledge from the power system analysis, a longer-term integrated planning approach is recommended. Although the next ten years may not suffer from the lack of inter-island interconnections, it is likely to become a problem in the following thirty years. Since the construction of inter-island interconnections takes years, integrated planning should start soon.

Moreover, the planning of the inter-island interconnections requires institutions concerning the use of seas and coasts. As found, regulations for the use of space for transmission only currently exist for land. Therefore, it is recommended to integrate regulations on the safety and agreements on using the seas for power transmission in the planning of inter-island interconnections. As demonstrated in the techno-economic optimization, the technical feasibility of the interconnections depends on geographical features, therefore it is important to have an integrated planning approach in which these features will be considered.

8.6.2 Institutional Strengthening for Investment

As found in the institutional analysis, the near-to-solo owner of all transmission infrastructure in Indonesia, PLN, does not have the financial resources to finance inter-island interconnections in the short term. Therefore, foreign investment is required. However, as found, currently the institutions in place for foreign investment in transmission infrastructure are lacking. Therefore, this study recommends establishing consistent and predictable policies that encourage long-term contracts and foreign investment in transmission infrastructure. Moreover, the procurement processes, as mentioned in the analysis, are crucial to expedite project development and reduce uncertainties that deter potential investors.

Another recommendation to lighten the found barriers is to add transmission capacity to the standardized contracts list, as described in subsubsection 8.4.2. The standardized contracts have been successfully used in other themes of the energy sector for public-private partnerships [Asian Development Bank, 2020b]. As found, a risk that is mentioned in public-private partnerships in Indonesia is the lack of transparency and stability therefore it is recommended that these two pillars are especially present in upcoming financing structures [FCDO, 2022]. Develop clear guidelines for contractual arrangements between public and private parties, promoting transparency and stability. Moreover, the standardized contracts for inter-island interconnections specifically should address technical requirements and revenue-sharing mechanisms.

Lastly, the attractiveness of investment in transmission capacity is low. Historically speaking, electrification rates were an important objective in development plans and therefore interesting for investment. However, as this study shows, transmission capacity like inter-island interconnections are a necessity for the net-zero target. Therefore, it is recommended that grid balance and renewable resources distribution are emphasized more in the national energy plans and reports [International Energy Agency, 2020a]s. One side of investment is stirred by the necessity of the investment. However, another side of investment is the profitability of the investment. Academic literature has not picked up that last topic yet for inter-island interconnection but what is worth noting is that in other countries, grid balancing is now a part of the electricity tariff. For instance, in Europe, the EU Commission has proposed a market reform that requires its member states to include a price for operational costs and grid balancing in their tariffs [European Commission, 2023]. This creates revenue for the development of transmission infrastructure and can make investment more attractive. Another option would be to incorporate the environmental benefits of renewables into pricing frameworks and the promotion of interconnections, which makes the investment more interesting. An example of this is the promotion of the interconnection between New York and Canada, which is promoted as an *'Innovative solution to address the biggest obstacle of clean energy'* [Hitachi Energy, 2023b]. Lastly, it is recommended to explore other sustainable financing instruments like green bonds to raise funds for transmission expansion in Indonesia.

8.6.3 Governance body dedicated to interconnectivity

As mentioned in the institutional analysis, a significant barrier to the development of inter-island interconnections is the lack of structures in place to guide and govern this complex infrastructure project. The development of inter-island interconnections involves a high degree of complexity and coordination, as it requires seamless integration between multiple regional offices of PLN and, among others, foreign investment. PLN operates through a national office and regional offices. The existing PLN operational structure, which often functions on a per-island basis, might not be optimally suited to oversee the intricate coordination required for interconnection projects. A dedicated governance body would streamline decision-making, project oversight, and cross-regional collaboration, reducing the risk of delays caused by bureaucratic inefficiencies.

While a step in the right direction is made with the compliance of grid codes of the individual power systems in Indonesia in ESDM 20/2020 [ESDM, 2020a], inter-island interconnection would require even more harmonization of technical standards, and operational procedures. A central governance body can facilitate this harmonization process by enforcing standardized practices across different regions and ensuring that all technical aspects align. This will enhance the overall stability and efficiency of the interconnected power system.

Another benefit of a dedicated governance body is that it can act as a central point of contact, fostering effective communication, alignment of interests, and a shared vision among stakeholders. This alignment is crucial for navigating the complexities of interconnection projects. This also provides focus since PLN has numerous responsibilities in the energy system, a dedicated governance body for interconnectivity can singularly focus on the successful planning, execution, and monitoring of inter-island interconnection projects.

The following figure Figure 8.9, shows a summary of the institutional design proposals that are proposed in this study, structure adapted from [Simanjuntak, 2021].

8.7 Validation of the design proposals

In this section, the validation of the design proposals is presented based on insights obtained from validation interviews with two experts in the field of energy systems and infrastructure, Professor Aad Correlje

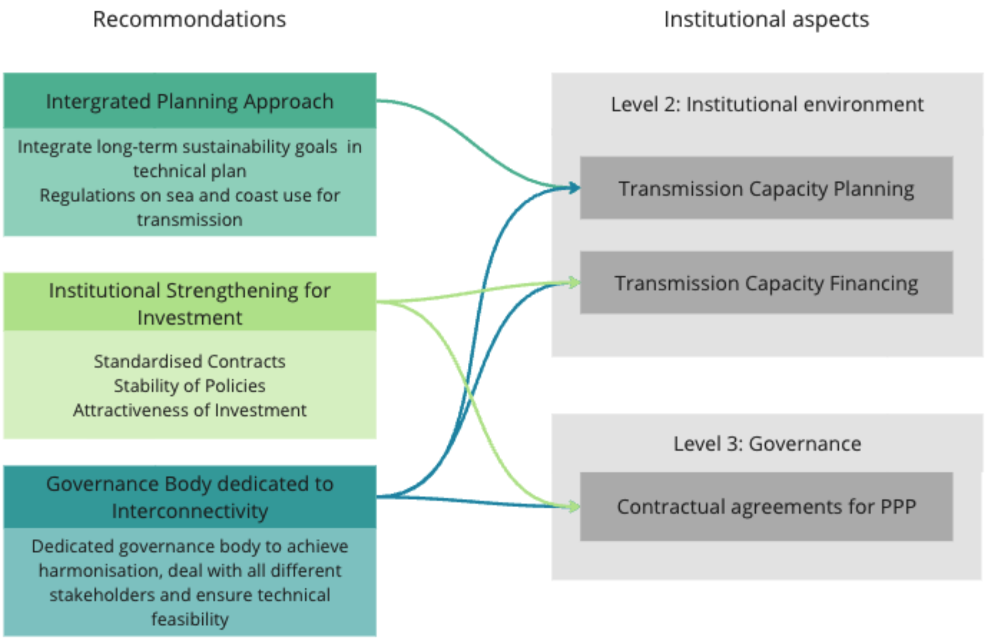


Figure 8.9: Summary of the proposed institutional design proposals as determined in this study following the Williamson framework

(2023)and Professor Laurens de Vries (2023). The transcript of the interviews can be found in Appendix D. The design proposals are described in the previous section: an Integrated Transmission Capacity Planning Approach, Institutional Strengthening for Investment, and the establishment of a Governance Body dedicated to Interconnectivity.

On the first design proposal, Professor Aad Correlje (2023)emphasizes the importance of comprehensive planning when it comes to energy systems. The stress is on the need for harmonizing short-term and long-term perspectives, considering technological advancements, spatial developments, and the integration of various timelines for changes. While not directly addressing the proposal, Aad's insights align with the core principles of an Integrated Transmission Capacity Planning Approach. Comprehensive planning that accounts for different aspects of the energy system is essential for sustainable infrastructure development. Professor Laurens de Vries (2023) discusses the complexities of planning for transmission infrastructure, particularly in interconnected systems. The focus is on highlighting the challenges of cost allocation and the need for careful phasing and planning. These challenges underscore the importance of adopting an integrated approach to transmission capacity planning, which involves considering technical, economic, and regulatory aspects within the broader energy system.

When discussing the second design proposal, Institutional Strengthening for Investment, Professor Aad Correlje (2023)underscores the role of standard contracts in legitimizing and ensuring investment security. The discussion is on the importance of creating a structured plan that can provide confidence to investors and reduce risks associated with unreliable political systems. His insights support the idea that strengthening institutional frameworks can enhance investment in the energy sector, aligning with the proposal for Institutional Strengthening for Investment. Laurens touches upon the role of national monopolies like PLN and their potential advantages and disadvantages, especially concerning energy policy and infrastructure development. The focus is on suggesting that strengthening institutions, particularly in the context of regulatory bodies and energy policy, could be crucial for creating an environment conducive to investment, affirming the proposal's significance.

On the last design proposal, a Governance Body dedicated to Interconnectivity, Professor Aad Correlje (2023)does not explicitly address the benefits of a dedicated governance body focused on interconnectivity, the discussion is on the role of Transmission System Operators (TSOs) and the need for collaboration at the European level indirectly supports the idea of having governance structures dedicated to managing and overseeing interconnectivity. The insights highlight the importance of coordinated efforts in infrastructure development, which resonates with the need for a dedicated Governance Body focused on Interconnectivity as proposed. Laurens discusses the complexities of collaboration for energy projects across countries and regions, emphasizing the challenges of cost allocation and coordination. The insights underline the importance of having a governance body that can facilitate and oversee interconnectivity efforts, especially in cross-border projects. This supports the need for a dedicated Governance Body focused on Interconnectivity as proposed.

8.7.1 Additional design proposals from the validation interviews

In addition to the validation of the design proposals, the interviews also highlighted the importance of some other institutional factors that will be described in this section. First of all, Professor Aad Correlje (2023)highlights the importance of long-term planning in the development of the system. He proposes that there should be a strategy for three different time perspectives, the short-term focus on the actual operations of the system, a short-term perspective focused on the immediate development of the system, including new connections, and a third perspective that is a long-term perspective that considers the expectations related to both supply and demand for electricity. These three perspectives should be constantly aligned with each other and regularly updated. He stresses the need to harmonize short-term and long-term perspectives, considering evolving technologies, spatial changes, and varying timelines for energy system transformations.

Following this, both Professor Laurens de Vries (2023) and Professor Aad Correlje (2023) address the importance of investment security. Professor Aad Correlje (2023)emphasizes the role of standard contracts in providing certainty to investors, while Professor Laurens de Vries (2023) discusses the challenges of private investments in infrastructure, especially in the presence of network effects. Furthermore, they both discuss the role of national monopolies, like PLN, and the challenges associated with politicization and short-term interests. They suggest that strong institutional frameworks are needed to ensure efficient infrastructure development and energy policy. Making plans or determining frameworks can make infrastructure planning break free from the risk of turbulent political influences. Moreover, when there is a detailed plan that shows that there are a lot of interconnection projects in the pipeline, this can create attraction for developers and investors. For interconnection specifically, this can mean that developers see less risk in investing in a new boat for cable laying.

Another interesting take is the highlight of complexity in collaboration by Professor Laurens de Vries (2023), he highlights that the collaboration for energy projects across countries and regions can be complex. He mentions that there are big challenges related to cost allocation, coordination, and the need for strategic thinking in interconnection projects. For instance, if the interconnection infrastructure will be financed through a part of the electricity sales of PLN, will the tariff needed to build the interconnection only apply to islands that will benefit from the interconnection? Or will this be paid by the country as a whole, these are things to think about. Another aspect of the ground for financing the system is the social benefit, as mentioned by Professor Laurens de Vries (2023). He emphasizes that interconnection infrastructure, while expensive, often provides societal benefits that outweigh the costs. These types of projects are usually not market commodities but are heavily regulated. Therefore, it might be favourable that PLN develops the interconnections themselves instead of through foreign project developers. Since, foreign development will usually aim for an economically viable price, not per se considering the societal benefit as much as a government body. Lastly, both experts mention corruption and risk management as an important aspect of the institutional design. They mention that there is a great risk of corruption in large infrastructure projects, and emphasize the need for risk management strategies and careful project planning to minimize these risks.

In this chapter, the results of the institutional analysis are presented. Starting with the outcomes of the stakeholder analysis, the chapter proceeds to explain the results of applying the Williamson framework to the specific case examined in this study. These results serve as the foundation for formulating design proposals, *which are subsequently validated through expert interviews with two distinguished professors. The insights derived from this analysis will be subjected to thorough discussion in Chapter 9, the discussion chapter.*

9 Discussion

This section first presents the discussion of the methodology and results of this study divided in five categories (9.1 - 9.5). Then, the discussion if proceeds to the the limitations of this study and specifically the used methodology subsection 9.6. Lastly, the reflection on the scientific and societal relevance of this study in are discussed in subsection 9.8. Which is concluded in recommendations to relevant actors that read this study in subsection 9.9.

9.1 The relevance of GIS analysis and shortest path calculations for energy system models

This study performs a techno-economic optimization through a combination of energy system modelling and geographical feature analysis. As previously mentioned, energy system modelling plays a crucial role in simulating and predicting energy flows and behaviours in various systems [Pfenninger et al., 2014]. The method used for this is in many cases linear programming whereas used generation technologies are projected on a map with transmission infrastructure as straight lines between them [Brown et al., 2018, Pfenninger and Pickering, 201
The addition of geographical analysis in the optimization process in this study can be compared to energy system model results without the explicit mentioning of the aspects. For instance, the first run of the Calliope model in this study and the projection of the Institute for Essential Services Reform (IESR) in Indonesia. The following Figure 9.1 shows the projected power capacity numbers for both projections under each other.

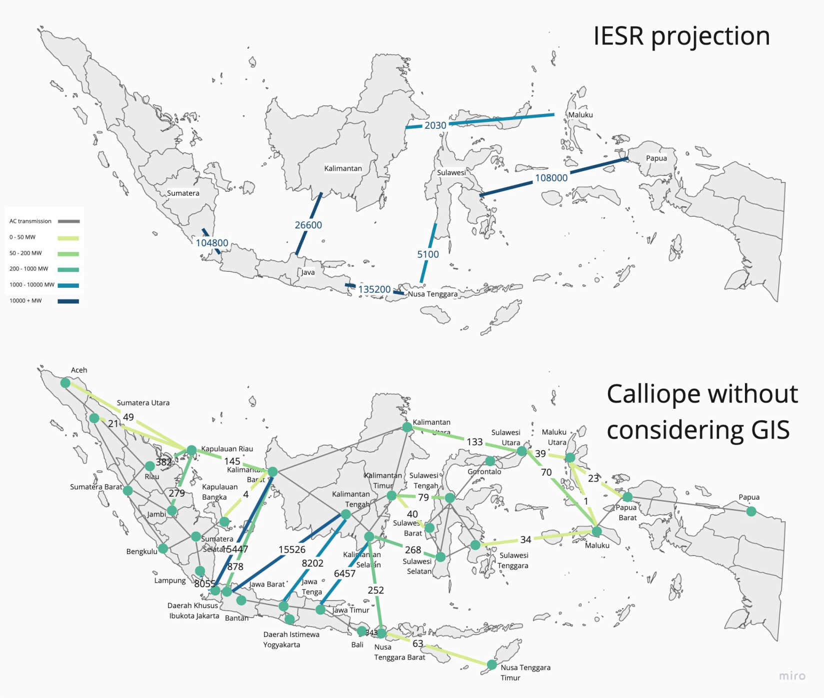


Figure 9.1: Capacity projections for two energy modelling studies without mentioning geographical features

As can be seen, these figures highly differ from each other and also from the feasible projection of this study. As described, the first run of Calliope, contains numerous interconnections that run through challenging areas such as high seismic activity and steep slopes. The interconnections in the projection of IESR also show high capacity interconnection between areas that are considered challenging in this study. For instance, the IESR projection shows an interconnector of 108000 Megawatt between Sulawesi and Papua (adapted from [IESR, 2023]), this area is an overall challenging area with a lot of steep slopes, deep seas and seismic activity. Moreover, the interconnection between Sumatera and Java is of high capacity in the projection of IESR. However, this study shows that that particular area is not considered feasible in this study when considering the geographical features.

9.1.1 The implications of not using geographical features in the optimization

The differences above indicate that there is a significant difference between the explicit inclusion of geographical features in the design of submarine power cables. Moreover, as described in the results, the needed capacity of the interconnections significantly changes when certain infeasible interconnections are removed. This is important to realise because the modelling of needed capacities is at the foundation of the current transmission infrastructure planning by PLN, as shown in Figure 8.4. The consideration of geographical features in the modelling process makes sure that high risks are identified early on in the planning process. As shown in section 5, the geographical features that are considered in this study are of high importance to prevent breakages and other implications to the submarine power cables [Wang et al., 2019, Ardelean and Forename, 2015]. The implication of not considering these geographical features early in the design process of submarine cable systems, like when only using Calliope or the projection by IESR, is that parts of the process will have to be revised since the geographical elements will most likely be studied later in the planning process. Therefore, including them early in the process will make the first ideas more realistic. Moreover, the inclusion of geographical aspects in the early stages of planning will emphasize their importance for submarine power cables. This will decrease the risk of failure throughout the further design and eventual implementation of the system.

9.2 Evaluating the single route scenario

In subsection 6.2, the scenario is opted to use a single route for the interconnection cables between Java and Kalimantan, instead of connecting the individual regions through the sea. There are various trade-offs to make on the choice of whether it would make more sense to use a single route or multiple interconnection routes. This section describes a selection of arguments for or against the single cable configuration.

On one hand, a single cable configuration offers notable advantages in terms of the efficiency of the construction of the cables. If all cables have the same start-and-endpoint, the facilities for building the cables can all be centred in one place. Moreover, cable laying companies demonstrate ships that can lay multiple cables at the same time, which will highly reduce the laying time compared to using different routes [Boskalis, , Van Oord,]. In addition, the eventual maintenance is also more centred and can therefore be less complex. Additionally, administratively, managing a single cable route may be simpler and require fewer regulatory approvals, allowing for quicker response times during maintenance or repair.

However, these efficiencies come with potential drawbacks. Concentrating all capacity on one route diminishes redundancy, increasing the system's vulnerability in the event of technical issues or external threats [Makrakis et al., 2023]. Geographical challenges or natural disasters specific to that location could disrupt the entire electricity supply chain. As one of the crucial geographic features to be considered in the design is seismic activity, and Indonesia is a highly seismic active country. The distribution of risk associated with seismic events should be considered in designing the routes [Makrakis et al., 2023, USGS, 2022]. Moreover, the environmental impact of such a concentration, including potential disruptions to marine ecosystems and nearby land areas, needs careful consideration. Studies indicate that the electric field of the cables can potentially have an impact on the marine environment and navigation devices [Ardelean and Forename, 2015].

9.3 Revising the selected geographical features

The four selected geographical features are selected following the literature review in section 5. These features are water depth (bathymetry), seismic regions, seabed inclination, and protected zones. Revising these selected features ignites the following discussion points.

9.3.1 Fast technological developments

First of all, the bathymetry, as mentioned by Wang (2021), the maximum water depth that is feasible at this moment is about 3000 meters deep. The maximum water depth of six years earlier was about 1500 meters as written by Ardelean (2015). Since this study looks at a projection of a scenario in 2050, it is arguable that the 3000-meter threshold is too constricting considering the fast developments of the past years. While this threshold is relevant at this moment, technological advancements and evolving industry standards are expected to be improved moving towards 2050. This argument can also be made for the categorization of the seabed inclination challenges. Companies like van Oord and Bosk regularly publish new submarine cable laying technology developments, like seabed preparation and dredging for problematic seabeds [Van Oord, , Boskalis,]. Therefore, the selection and categorization of the impact of these geographical features might be less relevant in a time span of almost 20 years.

9.3.2 Seismic activity

In this study, the recorded seismic activity of the seabed in Indonesia from 1970 onwards with a magnitude higher than 4.5 is used to explore which areas are at high risk of eruptions. In this study, the seismic activity is considered as a binary value, the activity is either present or not present on a specific part of the seabed. Although looking back at this determination, it might have made more sense to look at the seismic developments to see wether an area is active of not active. This reasoning is used in the study by Makrakis (2023), where the active seismic vault lines are used instead of eruptions [Makrakis et al., 2023]. Using active seismic vault zones might provide a more realistic view of the risk of seismic activity in a certain are. Nonetheless, the inclusion of seismic activity is an important aspect to consider.

9.3.3 Feasible versus challenging

Throughout this study, the term ’feasible’ is used to describe interconnections that meet the requirements outlined in section 5. However, it’s important to note that even if a cable doesn’t meet all these requirements, it might still be possible to implement it. Consider, for instance, areas where geographical features make cable installation challenging. Despite these challenges, the pressing need for the system may still make it feasible. The most significant example to illustrate this discussion point is the interconnection between Sumatera and Java in this study. The area between these two islands is not considered ’feasible’ by the selected geographical requirements of this study. However, the capacity as optimized by the energy system modeling software Calliope, is one of the highest of the system. The following figure shows a zoomed-in visualization of the geographical features on the seabed of this area.

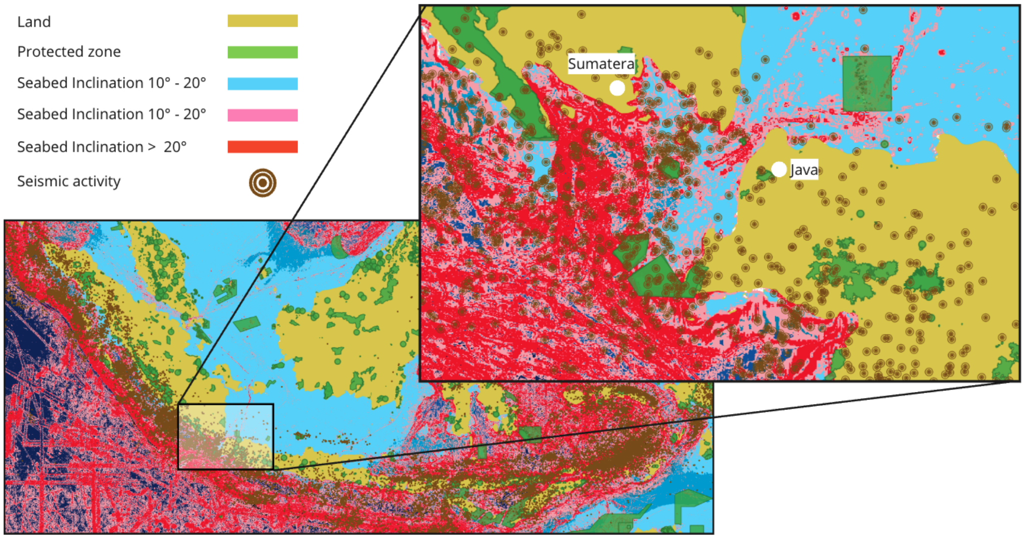


Figure 9.2: Geographical features of the area between Sumatera and Java, seabed slope and seismic activity

In Figure 9.2, In this image, you can see that the area between the two islands poses challenges due to steep seabed slopes and seismic activity. Consequently, an interconnector in this region is classified as ’non-feasible,’ and is removed from the energy system model. Thus, the next optimization of the energy system model shows that there will be more capacity needed between Kalimantan and Java, which makes up for the interconnection between Sumatera and Java. The area between Kalimantan and Java is considered feasible.

However, as discussed in subsection 9.3, technology advances quickly. Looking ahead, it’s possible that the area between Sumatera and Java may become suitable for implementing an interconnector. Therefore, one might argue that the term ’feasible’ doesn’t precisely capture the situation. The area between Sumatera and Java presents considerable challenges by today's technological standards. Yet, due to its high importance, as indicated by the energy system model's high capacity, and the rapid pace of technology, this region may still become feasible in the future.

9.4 The dynamics between islands

The dynamics between islands came up in both validation interviews and have been mentioned in the reviewed literature but are not considered in this study. As mentioned by Professor A. Correljé (2023), local geopolitics can highly influence the development of nationwide plans Appendix D. This considers the differences of power and authority between the islands. For instance, studies indicate that most decision-making is still made in the capital Jakarta, which is located on the island of Java. Whether this would mean certain islands will be favoured in the development of an interconnected system is something that is not mentioned or considered in this study. As described in section 8, only national plans are used in the institutional analysis since the interconnections are always between two regions. In order to investigate the differences and interests of the individual islands, the regional plans should also be considered. Moreover, Professor L. de Vries mentioned that in Europe, the plans for interconnection are also determined through the interest of the individual countries, not per se for the interest of the entire system as a whole.

Therefore, this study suggests that incorporating regional plans and recognizing the influence of local dynamics can contribute to a more holistic approach to infrastructure planning. This could help in identifying potential disparities and biases in the development of interconnected systems and lead to more equitable and effective solutions.

9.5 The integration of the techno-economic optimization results and the institutional analysis

In the previous chapters, the results of the techno-economic optimization and the institutional analysis are presented. Since these are described in separate chapters, it may seem as if these two perspectives do not influence each other. This section describes how these two parts influence each other and complement each other. First of all, techno-economic optimization provides a projection of a power system's potential functionality. However, the realization of these plans occurs at an institutional level, primarily within the context of development plans such as the RUPTL. These institutional plans are significantly shaped by political dynamics, including awareness levels and the allocation of financial resources. These political aspects influence the practical application of the techno-economic optimization results and are essential to understanding how models translate into real-world decisions [Pfenninger et al., 2014].

The next step in bridging the techno-economical optimization and the institutional analysis is the creation of a detailed implementation plan. This is also recommended in the validation interviews. As determined in the techno-economical analysis, there is a need for a high capacity of interconnection infrastructure, especially between Java and Kalimantan. Due to the high costs of such a system, there will probably be a phased execution of the system as a whole. As determined in the institutional analysis, Indonesia currently does not have the financial resources to develop a system like this. As highlighted by Professor Laurens de Vries (2023), the method for financing the interconnections can significantly influence their prioritization and sequencing. For instance, if the infrastructure is financed from the electricity tariffs of electricity users, a key question arises: will these tariffs apply solely to the islands that benefit directly from the interconnection, or will the entire country bear this cost collectively? How this financing is organized can also have an impact on the decision-making process regarding the sequence and prioritization of interconnections.

The exploration of inter-island interconnections in Indonesia may increase awareness and willingness among both the populace and decision-makers. As found in the Level 1 analysis using the Williamson Framework, the willingness of individuals and institutions to embrace changes in the electricity system can be a formidable barrier to successful implementation subsubsection 8.2.1. Positive findings regarding the feasibility of the sea route between Java and Kalimantan may stimulate greater collective enthusiasm for these changes in the electricity system.

To make the bridge between techno-economic optimization and institutional analysis even stronger, the AHP analysis can be further expanded. For instance, the willingness of a certain region to build an electricity station that serves as a start-or-endpoint of the interconnector could be taken as a weight for the design of interconnection routes. This approach, as suggested in related studies [Wang et al., 2019, Ardelean and Minnebo, 2023], offers a promising avenue to integrate institutional factors into the optimization process.

9.6 Limitations of the socio-technical optimization

9.6.1 The Calliope optimization results

Through the optimization using the Calliope model, the subquestions and main research questions of this research can be answered. The optimization with iterations results in a, for this study, feasible interconnections network in Indonesia. The results are feasible for the metrics as determined in the literature analysis and method of this study. However, it is worth noting that the subset of interconnections between Jawa and Kalimantan have gigantic needed capacities. As described, current HVDC systems peak at a capacity of 1200 MW, while the interconnections of this study reach up to 16000 MW, more than ten times more. Although technology companies claim that their new HVDC technologies have a power rating of up to 12000 MW [Hitachi Energy, 2023a], these technologies have not been implemented yet. Therefore, the question remains whether it is feasible to have either gigantic or multiple interconnections from one island to the other in Indonesia.

9.6.2 The Calliope optimization limitations

The Calliope optimization plays a dominant role in the determination of the feasible interconnections in this study. Especially through the results of the first run after which the most interconnections are removed from the analysis. Calliope is a well-proven energy system modelling tool that has been used in numerous publications and projects. However, it is arguable if this energy modelling software is the best selection for this specific study.

As explained, the costs are calculated through the energy capacity costs per megawatt. This number is coming from academic sources and is supposed to refer to the costs of transmission per megawatt. However, for the planning of transmission infrastructure and especially submarine infrastructure, the most expensive part is the construction of the transmission infrastructure. This part is well-discussed in the institutional analysis but minimally in the Calliope optimization. There is an option to add manually add the purchase price of transmission infrastructure to Calliope. However, due to this extra decision variable, the computational time of solving the model becomes so long that it is not possible to do this in the scope of this study. Therefore, it is worth noting that the use of another energy system modelling software tool might offer more realistic opportunities through optimization alone. Because, it is important to state here that because of the feasibility analysis of each run, the purchase costs are still considered.

Furthermore, in addition to the expenses, the Calliope optimization framework overlooks several crucial aspects of power system analysis. For instance, it fails to take into account factors like line loading within the system and the voltage levels of transmission lines conforming to the N-1 criteria [Venkatasubramanian and Tomsovic, 2004]. As mentioned by Maulida, daily blackouts occur in eight out of thirteen power systems in Indonesia [Maulidia et al., 2019]. This kind of aspect can be crucial in the planning of a transmission system [Venkatasubramanian and Tomsovic, 2004]. Given the significance of these features in assessing the feasibility of a power system, this limitation weakens the robustness of the analysis outcomes.

Lastly, as mentioned by Fodstad et al., energy modelling, especially when using scenarios, deals with significant uncertainty [Fodstad et al., 2022]. This study only uses two scenarios based on demand, which decreased the uncertainty of the results slightly but not to the extent of what is currently possible. Fodstad et al. propose the use of more advanced methods like stochastic programming or Monte Carlo analysis [Fodstad et al., 2022].

9.6.3 The AHP and shortest path analysis results and limitations

The AHP method in combination with the shortest path analysis is inspired by similar studies that investigate how submarine cables can best be designed and routed [Wang et al., 2019, Makrakis et al., 2023]. Therefore, this method is assumed to be a good match for these types of research questions. The determination of the AHP comparison matrices and ranking scores are also aligned with the aforementioned studies. The shortest path algorithm shows how the interconnection routes can avoid certain geographical features, for instance, lines of steep seabed inclination. However, as can be seen in the result section of the AHP analysis, the routing of the interconnections does not differ for the two created scenarios. This result is explainable when looking at the geographical feature GIS maps, in which can be seen that at the locations of the required interconnection lines, no significant challenges are present. This is partly due to the GIS feasibility study that was already performed during the Calliope optimization iterations.

One point of criticism for this section is the question of necessity, is it necessary to include the shortest path analysis to this extent when the geographical features are already considered in the Calliope optimization? The shortest path analysis does not provide any new insights into the feasibility of the interconnections and is in line with the Calliope optimization. The only thing that this analysis offers is a visual understanding of the possibilities of routing the cables and the insight that even when seismic areas are considered very important, the interconnections are still feasible.

9.7 Limitations of the institutional analysis

The institutional analysis results in the recommendation of three institutional adjustments which are found to improve the institutional setting for the development of inter-island interconnection. These design proposals are based on the literature and the analysis. However, there are aspects that are not considered in the design proposals due to scoping and time limits can be important for the feasibility of the design proposals. First of all, the consequences of using foreign investment. As briefly mentioned by the Asian Development Bank and Bridle, foreign investment can result in a significant debt [Bridle et al., 2018] [Asian Development Bank, 2020a]. Moreover, as discussed, inter-island interconnection is literally connecting neighbouring islands to each other. The institutional dynamics or differences between the different islands are not included in the results or design proposals.

The method used for the institutional analysis, as described in subsubsection 7.5.2, builds on a set of academic studies that apply the Williamson four-level framework in the context of the electricity sector [Scholten and Künneke, 2016, Simanjuntak, 2021, Kucharski and Unesaki, 2018b]. However, it's important to note that no previous academic work was found that applies the Williamson framework specifically to inter-island interconnections. Furthermore, this analysis focuses on the second and third levels of the framework, concentrating on specific aspects within these levels. This narrowing down of the analysis is due to time constraints, which leads to the main limitation of this approach. A comparison with the comprehensive study by Scholten et al. reveals that certain elements of electricity infrastructure development, not covered in this study, might influence the overall analysis. This limitation raises questions about whether the scope adequately captures all the relevant aspects and could potentially impact the strength of the proposed design proposals.

9.8 Reflection on the scientific relevance

The next section delves into the scientific contributions of this study, reflecting on its contribution to science. This section is structured into four key parts: firstly, an examination of the techno-economic optimization methodology and its implications; next, an exploration of the institutional analysis; subsequently, an integration of these two components; and finally, a reflection on the concrete findings.

9.8.1 Reflection on the techno-economic optimization methodology

As described in the methodology section of this part, section 4, the techno-economical optimization is a combination of two methods. First, an energy system modelling method using Calliope, combined with a geographical analysis using GIS analysis and an AHP shortest path method. These methods are both based on existing studies. As the Calliope model is built by PhD Jannis Langer (2023) and the combination of GIS analysis with an AHP shortest path is a method inspired by Makrakis (2023) and Wang (2021). However, there are two aspects that contribute to the existing methodologies. First and foremost, their combination into one study. As it is not possible to consider geographical elements in the Calliope model, the combination with GIS analysis is novel and demonstrated to be relevant. Secondly, the inclusion of power capacities in submarine power cable routing design is novel. By including the power capacities of the cables, a more realistic view is created on the submarine cable.

For instance, in this study, the Calliope model was not able to identify the challenges in the sea between Sumatera and Java. On the other hand, if only the GIS analysis and AHP shortest path analysis were used for the routing design, the results would not have included the significant high capacity needed along the route, which cannot be satisfied through one cable at this moment. These insights complement each other and lead to a more comprehensive view of what should be further researched or decided.

However, reflecting on the methodology, there is room for improvement in the integration of these combined methods. It would be great to have the option in existing energy modelling tools to include geographical features of the system, especially since RET potentials can be influenced by spatial circumstances. However, due to the computational power necessary to perform GIS analysis, this might slow down the energy modelling tools significantly. Lastly, it is worth mentioning that this methodology is designed specifically for Indonesia in this study, but can be used for any submarine cable design study. s

9.8.2 Reflection on the institutional analysis

The institutional analysis in this study is based on previous studies done by Simanjuntak (2021) and Itiki (2020). This method entails the application of the Williamson four-level framework, combined with the specific application to electricity infrastructure concepts by Scholten and Kunneke (2016). A first step of validating the findings of this analysis was carried out through validation interviews with Professors.

Reflecting on this methodology, the scientific relevance can mostly be seen in the found barriers. As the proposed design interventions can be used as inspiration for decision-makers on how to address the found barriers, the barriers themselves provide new insights into what there is to improve. These barriers can all be seen as individual problem statements for which a solution can be developed. This method has demonstrated to be able to provide insights in the current institutional setting and its found barriers.

9.8.3 Reflection on the integration of the techno-economic optimization and the institutional analysis

This study is built upon two parts, the techno-economic optimization and the institutional analysis. This combination is inspired by Simanjuntak (2021) but is a novel application to the topic of inter-island interconnections. This method takes a step in the direction of comprehensive engineering, in which not only the technical but also the societal and economic aspects are considered. As the discussion already indicated, the integration of these two parts is not as represented as could be in this methodology. The concepts that are analysed in the institutional analysis are derived from techno-economic optimization, which is an integration. However, there are possibilities to have the results of the institutional analysis present in the techno-economical optimization and the other way around. Researchers who want to apply a similar methodology should consider how to integrate the two parts beforehand.

9.8.4 Reflection on the integration of the techno-economic optimization and the institutional analysis

As described in subsubsection 2.2.5, there was an identified knowledge gap on the inter-island interconnection of the islands of Indonesia. This study has attempted to start filling this knowledge gap through the exploration of feasible interconnection technologies, routes and institutional barriers. Specifically, the study has provided insights into which interconnection capacities are necessary for the Indonesian electricity system in the future and which of these interconnections are feasible in terms of the geography they route through. This study established knowledge of which areas of the Indonesian seas are challenging for the implementation of submarine interconnectors and which areas are less challenging. Moreover, this study can be used as a foundation for other studies on the topic to dive deeper into the configuration of the cables. For instance, the trade-offs between using a single route for the submarine interconnectors or a distributed routes alternative.

Another academic contribution is achieved through the findings from the institutional analysis, the found barriers and the proposed design interventions can be used for future research in the case of Indonesia. Additionally, they can be used as inspiration by researchers who investigate similar systems in other countries or of other scales.

9.9 Reflection on the societal relevance and recommendation for relevant actors

As described in section 1, interconnecting the islands of Indonesia through inter-island interconnections is a crucial element of the country's energy transition. As highlighted throughout this research, Indonesia has set ambitious goals to achieve net-zero emissions by 2060. Given its position as the fourth most populous country globally, this transition holds significant implications for the planet as a whole. The primary focus of this study was to investigate the feasibility and challenges of inter-island interconnections, specifically aimed at facilitating the integration of renewable energy technologies. And research towards this system, such as this study, is important because it allows Indonesia to integrate more renewable energy technologies, which is in line with the seventh Sustainable Development Goal of 'Affordable and Clean Energy' [United Nations, b]. The societal relevance of this research lies in its potential to transform Indonesia's power system into a net-zero system. By interconnecting the islands, access to renewable energy sources can be unlocked, benefiting many areas of the country that do not have equal potential for renewable resources. The ultimate goal of this research is to have a positive impact on Indonesia's energy transition by enabling the implementation of renewable energy technologies and promoting sustainable development.

Reflecting on this objective the following points can be made. The conclusions from this study demonstrate that inter-island interconnection is possible in Indonesia and the most important routes are feasible for the selected geographical features. Moreover, the institutional environment is analysed and design proposals are formed. The knowledge obtained through this study aims to the described objective of enabling Indonesia to implement renewable energy technologies. Therefore, it can be stated that this study stayed in line with the aforementioned objective of having a positive impact on Indonesia's energy transition.

Based on the findings obtained, the objective of this research is to offer valuable insights to key actors in Indonesia, enabling them to make well-informed decisions regarding the design and implementation of inter-island interconnections. In this regard, the following section presents a set of recommendations tailored to different actor groups, aimed at positively influencing decision-making processes toward the realization of a net-zero emissions system.

9.9.1 The Indonesian Government

- Ensure that national policies and regulations are aligned with the goal of achieving net-zero emissions by 2060 and inter-island interconnection. This includes providing clear incentives and support for the development and integration of renewable energy sources through inter-island interconnections. Moreover, make plans that will be fixed and have limited connection with the polictal changes over the coming years.
- Allocate substantial funding and resources to support the planning and implementation of inter-island interconnections. Explore opportunities for public-private partnerships to secure necessary investments.
- Develop a comprehensive infrastructure plan that prioritizes inter-island interconnections as a critical component of the transition to renewable energy. Consider the long-term benefits for the country's energy security and economic development. Make sure that the social benefits of inter-island interconnections are explicit and considered in planning.

9.9.2 PLN

- Make sure that the short-term planning, which also applies to the 10-year planning of the RUPTL, considers the longer-term electricity demand and generation predictions. This will most likely highlight the need for inter-island interconnection.
- Create a long-term, detailed road-map for the implementation for inter-island interconnections, not only will this decrease the risk of political influence but also be attractive for investment and an invitation for submarine cable developers to gather resources.
- Make sure that the design and planning of the inter-island interconnections considers the geographical features as described in this study. The earlier the better, to prevent re-visioning and to mitigate risk early on in the process.

- Invest in the training and development of technical personnel with expertise in HVDC technology and renewable energy systems to ensure the successful operation of interconnections. Since, the scale of capacity as proposed in this study is of a great scale.

9.9.3 Submarine cable developers

- Invest in sufficient resources to meet likely high demand of upcoming submarine power cable projects in Indonesia. Collaborate with local experts, like PLN, to navigate and create innovative solutions for the the unique challenges of Indonesian waters, such as seismic activity.
- Make sure to consider with the hesitation of the Indonesian populace to inter-island interconnection. Engage with local communities along the cable routes to address their concerns, provide information about the projects' benefits, and ensure a smooth installation process.

This chapter serves as the discussion section, dedicated to the examination of both the results and the methodology employed in this study. Additionally, it delves into the scientific contributions and societal relevance of the findings. The chapter concludes with recommendations tailored for the involved actors engaging with this study. The subsequent chapter will mark the culmination of this study, as it presents the conclusions drawn and outlines ideas for future research.

10 Conclusion

This study has attempted to investigate the feasibility and possibilities of developing HVDC inter-island interconnections in the power system of Indonesia between neighbouring islands. This is firstly done with a techno-economical analysis. Secondly with an assessment of the institutional context and its barriers for the development of such a system. The following chapter describes the answers to the defined research questions as stated in subsubsection 2.2.5.

10.1 Answering the sub-questions

This section contains the answers for the four subquestions

10.1.1 Technical and economical requirements for interconnectors

The first subquestion is the following:

> *"1. What technical and economic requirements are critical for the feasibility of inter-island power interconnectors?"*

Inter-island power interconnections are submarine power transmission technologies. Currently, HVDC power transmission cables are mainly used for this objective because of efficiency and construction advantages compared to HVAC transmission. The technical requirements for these cables are that they can currently be up to 1000 kilometres and can have a power rating of up to 1200 MW. The starting power capacity of when it would make economic sense to build an HVDC submarine transmission cable is 100 MW, although most current systems range from 500 and 1200 MW. Then, the literature assessment gave insights into various geographical features that are important for the possibilities and feasibility of constructing inter-island interconnections. From this assessment, the following four geographical were found to be most important. For each geographical feature, the following section will describe the requirements to be feasible for inter-island interconnection.

First of all, the depth of the water (bathymetry) where submarine power cables are installed is an important factor. Deeper waters make the installation more expensive and less economically feasible. It also makes it harder to manoeuvre the trench-cutting equipment and recover the cables. Deep-water conditions increase the hydrostatic pressure and add complexity to the service. The maximum water depth that can currently be crossed is up to 3000 meters. However, the deeper the water, the higher the costs. Therefore, it is favourable to route interconnections through water shallower than 1500 meters deep. Secondly, the seabed slope is another significant geographical feature. Steeper slopes can stress cables and complicate trench-cutting equipment operation during installation. Categorizing seabed slopes based on degree helps assess potential challenges. Therefore, this study found that the seabed slope should be less than 20 degrees for the interconnector route to be feasible. The next geographical feature is seismic regions. These areas are prone to seismic activity, such as earthquakes and volcanic eruptions, which must be avoided to prevent damage to submarine cables. The "ring of fire" in the Pacific region is particularly relevant, but even within Indonesian national seas, certain regions can pose risks. Lastly, environmental sensitivity requires the avoidance of protected areas. Minimizing the presence of cables in these zones reduces the risk of damage to the protected zones.

Economically, cable length emerges as the most influential factor in inter-island power interconnection design. It significantly dictates the resources required for interconnection development. Therefore, for an effective techno-economic optimization of interconnections, the overarching objective is to minimize the overall cable length.

10.1.2 Feasible routes for interconnectors in Indonesia

The second subquestion is the following:

> *"2. What are feasible and necessary interconnection routes to interconnect neighbouring islands to each other in the power system in Indonesia?"*

There are multiple interconnections that have been found feasible for power transmission in Indonesia by the method used in this study. The metrics used for the feasibility study are the requirements from the previous section and the selection of the Calliope optimization. The most significant needed power capacity between the islands is between Kalimantan and Jawa. The found interconnections vary slightly between the scenario of low fluctuating demand or highly fluctuating demand. The routes can best be seen in section 6. The following list will describe which interconnections have been found feasible in this study. For the low fluctuating demand scenario: between Kalimantan Barat and Daerah Khusus, between Ibukota Jakarta and Kalimantan Tengah, between Jawa Tengah and Kalimantan Selatan, between Jawa Timur and Kalimantan Tengah, and between, Kepulauan Riau and Riau. The high-fluctuating scenario has the same list except for the addition of the interconnection between Kalimantan Barat and Jawa Barat.

10.1.3 Institutional barriers

The first subquestion is the following:

> *"3. What are the institutional barriers to the development of an inter-island interconnected power system in Indonesia?"*

The insights derived from the literature review, using the Williamson four-level framework and detailed in subsubsection 8.3.2, reveal a major obstacle: the absence of comprehensive plans for inter-island interconnections within the RUPTL (Electricity Supply Business Plan). Additionally, the lack of guiding institutions to facilitate this planning process further adds to the challenge. When it comes to financing transmission capacity, as described in Section subsubsection 8.3.4, it becomes evident that a notable barrier is the lack of viable financial structures capable of funding the essential transmission infrastructure needed to achieve renewable energy objectives. Moreover, the existing structures fail to attract necessary foreign investment.

In the context of the third-level analysis within the Williamson framework, which scrutinizes contractual arrangements between public and private entities (Section subsubsection 8.4.2), a clear obstacle emerges which is the absence of institutional frameworks that promote such collaborations. Notably, the forthcoming regulations in this domain also contribute to an atmosphere of uncertainty.

10.1.4 Institutional design proposals

The last subquestion is the following:

> *"4. What are the needed institutional adjustments to promote an inter-island interconnected power system in Indonesia?"*

First of all, this study recommends using a more integrated transmission planning approach. This study recommends prioritizing interconnections in all national plans, emphasizing their role in achieving renewable energy goals. An integrated planning approach should start soon to avert challenges that might arise in the next three decades. Regulations for sea use in transmission planning should also be included.

The second recommendation is the strengthening of investment frameworks. To attract foreign investors, clear and consistent policies are needed, along with streamlined procurement processes. Including transmission capacity in standardized contracts and enhancing investment appeal through renewable energy benefits can further encourage funding. Exploring tools like green bonds can also fund transmission expansion.

The last proposed recommendation is to create a governance body dedicated to interconnectivity. A key barrier is the lack of a dedicated structure for guiding interconnection projects. Establishing a governance body can streamline decision-making and coordination. This body can harmonize technical standards, ensuring a stable interconnected power system. It can also serve as a communication hub, aligning stakeholders' interests and focusing solely on successful interconnection planning and execution.

10.2 Answering the main research question

Revising the main research question:

> *"Which inter-island interconnection routes are feasible to accommodate renewable energy technology integration in Indonesia and what are the needed institutional adjustments for fostering such an interconnected system?"*

First of all, inter-island interconnections are necessary for achieving Indonesia's renewable energy targets and ensuring a stable and reliable power supply. Based on the assessment of geographical features, several critical requirements emerge for the feasibility of these routes. The depth of water, seabed slope, seismic regions, and protected zones all play significant roles. The depth of water should ideally be shallower than 1500 meters to minimize costs. The seabed slope needs to be less than 20 degrees to ensure proper cable installation. Avoiding seismic regions and protected zones is crucial to prevent damage and maintain a healthy marine environment.

Following up on that, there are multiple interconnections that have been found feasible for power transmission in Indonesia by the method used in this study. The found interconnections vary slightly between the scenario of low fluctuating demand or highly fluctuating demand. The routes can best be seen in section 6. The following list will describe which interconnections have been found feasible in this study. For the low fluctuating demand scenario: between Kalimantan Barat and Daerah Khusus, between Ibukota Jakarta and Kalimantan Tengah, between Jawa Tengah and Kalimantan Selatan, between Jawa Timur and Kalimantan Tengah, and between, Kepulauan Riau and Riau. The high-fluctuating scenario has the same list except for the addition of the interconnection between Kalimantan Barat and Jawa Barat. These interconnections are mainly routed through the sea between Jawa and Kalimantan, which is considered a feasible area by this study. The visualisation of routes can be seen in the following Figure 10.1.

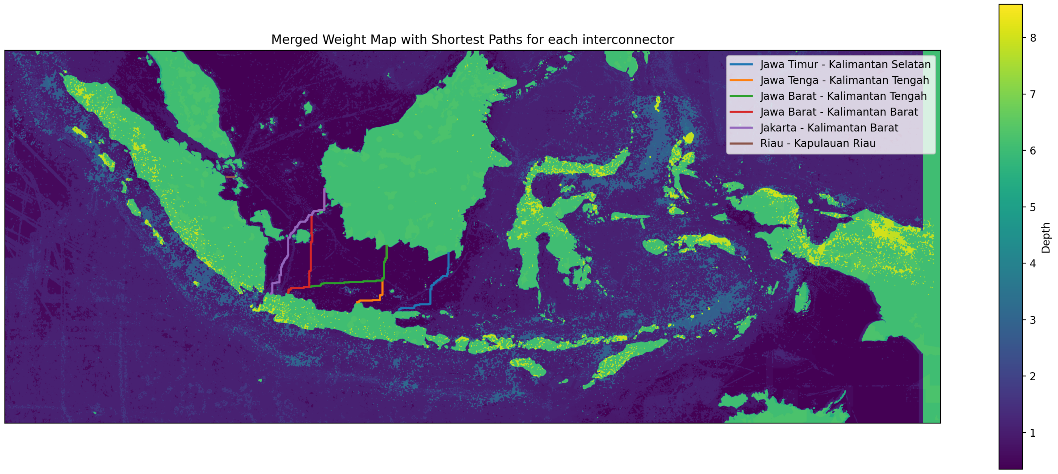


Figure 10.1: Visualisation of interconnection routes found in this study

On the institutional side, various barriers are found that need to be adjusted to improve the possibilities for inter-island interconnectors. The absence of comprehensive inter-island interconnection plans in the RUPTL constitutes a significant barrier. To address this, an integrated planning approach is recommended, emphasizing interconnections' importance for renewable energy goals and promoting integration into the RUPTL. Institutional strengthening is needed for foreign investment, with the establishment of consistent and predictable policies encouraging long-term contracts and financial support. Clear guidelines for contractual arrangements between public and private entities should be developed, ensuring transparency and stability. Enhancing the attractiveness of investment through grid balancing emphasis and exploring sustainable financing instruments like green bonds can further support interconnection projects.

10.3 Recommendations for future research

Next to the design interventions and findings from this study. This study can also be used as an inspiration for future research. The following section will describe four ideas for future research on the topic of inter-island interconnections in Indonesia.

First of all, it would be interesting to see the results of a study that is specifically directed to the power flow of the power system. As described in section 9, there are various requirements of power systems that have not been included in this study. For example the N-1 criteria, the voltage and the line loading of the power system. A study on this will provide a more in-depth review of which interconnections are feasible.

Secondly, it would be insightful to research the operational challenges of an interconnected system. For instance, the day-to-day balancing of the power system, the application of smart grid technologies and the potential risk of cyber security challenges to ensure a reliable and secure energy power system.

The third idea for future research would be to zoom into social engagement and public perception of inter-island interconnections in Indonesia. This would include the implications of inter-island interconnections on local communities and economies. For instance, the assessment of potential job creation, local economic development, and social acceptance of the interconnected system. The literature reviewed in this study has mentioned that the socio-cultural differences between the islands could be a challenge for the interconnected system [Ordonez et al., 2020].

Lastly, it would be valuable to asses other archipelago countries. Either for testing the approach taken in this study to other countries or to compare the proposed system with other island nations or regions that already have implemented inter-island power interconnections.

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A Literature Study

Table A.1: Literature review overview

ID	Article	Year	Take-away on interconnection
1	Power System Planning Assessment for Optimizing Renewable Energy Integration in the Maluku Electricity System [Tumiran et al., 2022a]	2022	Interconnection system between Maluku Island and surround islands is a feasible solution using HVDC lines and a power system model.
2	Modelling low carbon electricity generation of an integrated ASEAN power grid [Atmo et al., 2022b]	2022	Interconnection demonstrates benefits between countries in South-East-Asia. In the scenario of high carbon taxes, Indonesia is predicted to export renewable generated electricity through interconnection.
3	Transmission expansion planning for the optimization of renewable energy integration in the sulawesi electricity system [Tumiran et al., 2021]	2021	Indonesia's transmission system needs to be expanded in order to meet the demand. Within the Sulawesi system, two power grids need to be connected in order to implement more RET.
4	Deep decarbonization of Indonesia's energy system A pathway to zero emissions [**?**].	2021	Inter-island interconnection is necessary to satisfy the demand of Indonesia in a deep-decarbonized scenario. A Model based on demand and generation predictions determines the size of the interconnections.
5	Techno-economic analysis of remote microgrid and high voltage interconnected grid development in isolated area [Putra et al., 2020]	2020	On Seram Island, a remote microgrid is more beneficial than using interconnection to the main power grid to achieve the objectives of RUPTL development plan in this area.
6	Frequency stability and under frequency load shedding of the Southern Sulawesi power system with integration of wind power plants [Arief et al., 2020]	2020	Due to their intermittent nature, two big wind power plants in Southern Sulawesi might disconnect from the grid which they are interconnected to. If this happens, the frequency of the grid needs to be stabilized.
7	The Design of Kalimantan Transmission System Interconnection in Electrical Stability Perspective [Ardyono et al., 2019]	2019	Interconnection within the power systems of Kalimantan improves the access to renewable sources. Moreover, if the correct technologies are used, disturbances will not cause blackouts on the interconnected grid.
8	Study of AGC in the Sarawak - West Kalimantan Interconnected Power System under Deregulated Scenario [Sutardi et al., 2019]	2019	Through connecting West Kalimantan tot the other countries on the island, an optimal dispatch strategy can be implemented. Which will result in better supply-demand balance.
9	Optimal power flow for power system interconnection considering wind power plants intermittency [Ajami et al., 2019]	2019	In order to build large wind power plants in Sulawesi, there should be development in the planning of new infrastructures. Since the intermittent dynamics of the park can cause overload and disturbances on the current grid.
10	Overcoming barriers to solar and wind energy adoption in two Asian giants: India and Indonesia [Burke et al., 2019]	2019	Interconnection between islands in Indonesia would boost the country's ability to handle solar and wind sources.
11	Power system decarbonisation with Global Energy Interconnection – a case study on the economic viability of international transmission network in Australasia [Wang et al., 2018]	2018	An interconnection between Australia and Indonesia has significant economic and security benefits for both countries. Even though the interconnection is a big investment.

B Saaty fundamental scale of absolute numbers

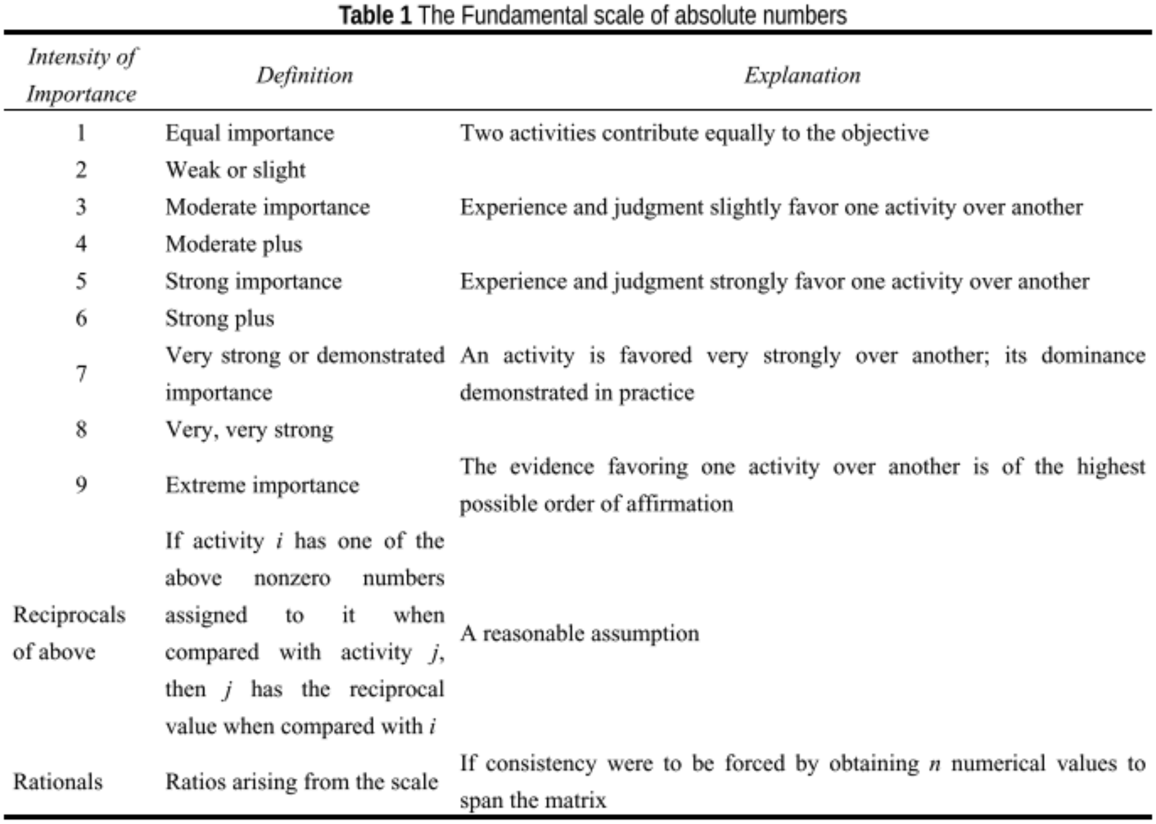

Table 1 The Fundamental scale of absolute numbers

Intensity of Importance	*Definition*	*Explanation*
1	Equal importance	Two activities contribute equally to the objective
2	Weak or slight	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity *i* has one of the above nonzero numbers assigned to it when compared with activity *j*, then *j* has the reciprocal value when compared with *i*	A reasonable assumption
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining *n* numerical values to span the matrix

Figure B.1: The Fundamental scale of absolute numbers

C HVDC interconnector distance between provinces used in the Calliope model

Province 1	Province 2	Distance (km)
Bali	Nusa Tenggara Barat	135
Kalimantan Barat	Daerah Khusus Ibukota Jakarta	790
Kalimantan Tengah	Jawa Tengah	690
Kalimantan Selatan	Jawa Timur	550
Kalimantan Selatan	Sulawesi Selatan	550
Lampung	Banten	180
Kepulauan Riau	Riau	310
Nusa Tenggara Timur	Nusa Tenggara Barat	810
Aceh	Kepulauan Riau	924
Sumatera Utara	Kepulauan Riau	609
Jambi	Kepulauan Riau	315
Sumatera Selatan	Kepulauan Riau	480
Kalimantan Barat	Kepulauan Riau	600
Kalimantan Barat	Jawa Barat	827
Kalimantan Tengah	Jawa Timur	610
Kalimantan Selatan	Bali	590
Nusa Tenggara Barat	Kalimantan Selatan	615
Kalimantan Selatan	Sulawesi Barat	460
Kalimantan Timur	Sulawesi Barat	315
Kalimantan Timur	Sulawesi Tengah	380
Kalimantan Utara	Sulawesi Utara	844
Nusa Tenggara Barat	Sulawesi Selatan	616
Kalimantan Tengah	Jawa Barat	865
Sulawesi Utara	Maluku Utara	320
Papua Barat	Maluku Utara	480
Maluku Utara	Maluku	500
Maluku	Sulawesi Utara	742
Maluku	Papua Barat	300
Maluku	Sulawesi Tenggara	850

Figure C.1: List of the HVDC interconnector distance between provinces used in the Calliope model in kilometers

D Validation Interviews

This section provides the transcript of the two validation interviews ordered per category. The interviews were semi-structured, they were guided by the following questions, and the conversation flowed from there.

1. Introduction - What is your link with the institutional side of electricity systems?
2. Method - What are your thoughts on the method used to construct the institutional recommendations for this study?
3. Analysis - What are your thoughts on the three analysed aspects related to electricity transmission development (Planning of transmission infrastructure, financing of transmission infrastructure and contractual arrangements between public and private parties)?
4. Recommendations - What are your thoughts on the three proposed recommendations in this study, do you think these would improve the institutional setting for inter-island interconnection in Indonesia?
5. Recommendations - What do you think would improve the institutional setting even more for inter-island interconnection in Indonesia?

D.1 Aad Correlje

Aad Correlje - Introduction

My connection with the institutional side of the electricity system actually stems from a long-standing development. It all began when I started with the oil industry, wanting to understand how the oil industry was structured, how it operated, how it evolved, how various aspects of the oil industry in different countries worked in specific ways, and how they were organized. After completing my doctoral thesis on this subject, I turned my attention to the gas industry, first in the Netherlands and then expanding to Europe and the global gas industry. This was also influenced by developments related to LG and similar organizations.

Simultaneously, I began to delve into the electricity industry, particularly with Laurens de Vries. We collaborated on research and attempted to establish a framework to comprehend the development, especially the liberalization of electricity markets worldwide. This framework has been widely used and cited, providing a structure for understanding the organization of liberalization in different countries and the extent to which they implemented it.

Subsequently, the energy system, including electricity, gas, heat networks, and particularly the electricity system, underwent significant changes. Sustainability became a focal point, along with the rise of decentralized generation, wind farms, and storage solutions. The market perspective shifted from being primarily static and efficiency-oriented to one focused on expansion, change, and adaptation. This perspective remains a central aspect of my thinking about energy systems.

At the same time, starting from my doctoral thesis in the early 1990s, I was exploring ways to analyze, understand, and describe the organization, structure, and functioning of these systems. This approach went beyond the traditional economic perspective of liberalization, encompassing technical, social, political, and regulatory aspects, within the context of technology, spatial considerations, and technology integration across different countries, including islands like Indonesia.

Aad Correlje – Long-term Planning

These long-term developments should ideally be reflected in the institutions. Three distinct time perspectives can be identified within institutional structures. Firstly, a very short-term perspective ensures that the system functions smoothly, ensuring the generation, transmission, distribution, and sale of electricity today and tomorrow, with parties paying for these services.

Secondly, a short-term perspective deals with the immediate development of the system, including new connections, such as those required for wind farms or increased demand from users. This necessitates an operational plan outlining what needs to be built or designed soon, with a focus on organization, financing, and connection.

Thirdly, a long-term perspective is needed, considering expectations related to both supply and demand for electricity. This perspective also accounts for spatial developments, such as the emergence or decline of specific activities in regions. Flexibility is crucial, allowing for adjustments and adapting to changing circumstances, including the availability of primary energy sources. Different islands may have varying timelines for these changes, which requires a phased approach.

In summary, these three perspectives must be harmonized, providing a comprehensive planning framework that accounts for the complex interplay between technology, economics, politics, and institutions.

Aad Correlje - Phasing

The challenge often lies in the transition phase, as people tend to think about the end stage of a transition without considering the actions needed to get there. The process towards 2050 is essential, but one must also plan for intermediate steps. Infrastructure projects, like building high-voltage cables, take time and require phased planning, investments, and coordination. Therefore, a planning approach with intermediate milestones becomes crucial to ensure the successful realization of long-term goals.

Aad Correlje – European Organization

From a European perspective, Transmission System Operators (TSOs) play a critical role. These operators, such as TenneT in various European countries, collaborate and form European organizations. They gather long-term predictions and insights from national TSOs, sharing this information at the European level. Additionally, insights are collected at the ENTSO-E level, which impacts interconnection needs.

In Europe, TSOs can charge regulated tariffs for electricity transmission, a significant portion of electricity bills. These tariffs cover the costs of maintaining high-voltage systems and transmission infrastructure. Moreover, companies buying electricity and seeking to transport it between countries must determine entry and exit tariffs, depending on capacity and demand. This system involves various tariffs, but they all contribute to financing interconnections between countries. In your case, with a single island and one TSO, you may consider implementing separate transmission tariffs that align with the capacity and requirements of each region. This would encourage efficient interconnection planning.

Aad Correlje - Global Fund
In considering the closure of coal mines, a key source of revenue and employment, it is essential to anticipate potential social and economic disruptions. Sudden closures can lead to social unrest, which has been observed in many regions worldwide. To address this, a comprehensive plan should identify alternative economic activities and stimulate their development in affected areas. This approach aligns with goals for sustainable energy generation and distribution.

One could plan for each region to identify potential economic alternatives and connect them with energy needs, thus creating development plans. These initiatives could be integrated into existing carbon financing measures, ensuring a holistic approach to reducing coal production, promoting modernization, and improving electricity provision. This planning would impact long-term strategies, considering the regional context and specific development needs.

Aad Correlje - Standard Contracts
Standard contracts play a vital role in legitimizing and ensuring investment security. They establish certainty within a planning context. Without such contracts, uncertainty prevails, leading to higher return-on-investment demands from investors to mitigate risks. A structured plan, separate from immediate political influence, enhances investor confidence and reduces risks associated with unreliable political systems.

Furthermore, when dealing with relatively unstable political environments, standard contracts can serve as a means to anchor decisions within a plan structure, creating distance from direct political influence. This can ultimately make it less risky for investors to engage in areas where political reliability is uncertain.

Aad Correlje - Method
While reading your text, I wondered about the potential impact of power dynamics between islands, local governments, politicians, and those managing the islands. These dynamics are relatively neutral in your description, considering all as part of Indonesia. However, it's plausible that significant power disparities exist between the various stakeholders, each with different interests and objectives.

Incorporating these nuances into your text may be challenging, as it would require a more in-depth examination of these differences and their complex interplay. Rather than delve deeply into this issue, you could acknowledge its presence at various points in your text. You could highlight that the effects of local geopolitics and power dynamics often play a pivotal role in shaping opinions, perceptions, and interpretations.

For further research, you can suggest exploring the influence of these dynamics and the complexities they introduce. This would be an essential area for someone to investigate, requiring a comprehensive examination of local geopolitics and how they impact the energy transition process.

Overall, it's best to keep this topic as a recommendation for future research and as an aspect that should be carefully considered by those investigating the energy transition in Indonesia.

D.2 Laurens de Vries

Laurens de Vries - HVDC Cables
Regarding HVDC cables, they are technically different. Normally, it's always direct current. But when it goes underwater or spans more than a few kilometers on land, it's usually alternating current. The costs depend on size and converters, which are large installations. Onshore, you don't easily allow private investments individually because of complex network effects. However, with direct current and converters, you can. With alternating current, you can turn it on and off, making it more controllable. In the Netherlands, we have connections to England and other separate business units, allowing both PLN on land and private companies to operate. If you tell a private company to invest in transmission between points A and B and recover the investment from price differences, they might not invest enough. A classic economic problem, as monopolists offer too little of the product to keep prices high. So, as a government, you can bid it out. They may not earn price differences, but they may earn it with congestion, which we finance. So, there are three options: PLN does it internally and can charge customers, the government manages it (similar to the first option), or it's tendered out to private companies. For HVDC, it's essential because it's controllable, and the

standard is around 1000 megawatts.

Laurens de Vries - Collaboration for HVDC Investment

Climate funds, I'm not well-versed in that; it's political economy. In Europe, we are not very strategic about our network development. What you mention is similar to what we should do in the North Sea. It's an idea to exchange energy between North Sea countries, with a focus on wind energy. However, this is progressing slowly. Belgium talks to Denmark but not with the Netherlands due to conflicts around the Westerschelde Antwerp area. It's somewhat like schoolyard cliques. There's a lack of strategic thinking. On the European mainland, there's a senior network that plans, but it's a sum of what all member states want. They try to include projects, especially if they get recognition as a Project of Common Interest, which allows them to access European subsidies. Financing still tends to be bottom-up. Fundamentally, if Australia connects to Malaysia, there's a challenging cost allocation problem. Australia might benefit from exporting solar energy while Indonesia might benefit at other times. It's challenging to quantify these benefits and determine each party's share. You can't solve it unless the benefits are significant for everyone. You must undertake large projects that work, and each step should be valuable on its own. Interconnection infrastructure isn't necessarily profitable in a traditional sense; it's expensive. However, for the society, the benefits often outweigh the costs. These are not true market commodities; they are heavily regulated.

Laurens de Vries - PLN's Role

In theory, having a national monopolist like PLN can be an advantage, but it's highly politicized due to its essential services. The top management is close to politics, and short-term political interests often come into play. Energy policy is also poverty policy. It would be smart, for instance, to provide cheap energy to low-income households, but it's politically expedient to offer everyone low prices. However, this can hinder investment capital. Some Indian states offer cheap electricity for the first 500 kilowatt-hours per year and then gradually raise the rates. This can cross-subsidize the poor with the rich. This approach requires political support because it places a heavier burden on wealthier, more influential citizens. The advantage is that it raises funds to create a more reliable system. Infrastructure development isn't liberalized; it typically remains a monopoly with regulated costs.

Laurens de Vries - Interconnected System

I believe it's feasible, but it requires phases. Currently, most of Indonesia relies on coal. You'll initially expand local sustainable energy production and gradually transition towards electrification. As consumption rises, you'll try to meet it with local production. When it becomes impossible to expand locally, interconnection becomes necessary. Planning can help determine the timing and potential cost savings. Liberalization of the electricity market isn't straightforward due to its complexity and transaction costs. Some form of bundling at the high-voltage level, with industrial consumers and utility companies on the consumer side, can create a manageable market.

Laurens de Vries - Market Structure

It's important to involve all stakeholders. The big question is whether PLN remains a full monopolist or focuses on the networks, leaving sustainable generation to the market. Another question is who becomes the buyer of this power – PLN or large consumers? These are the variables. Within the network, central planning will continue in some form. It can be top-down or involve more stakeholder engagement. Economic efficiency is a complex issue; if you socialize network costs, you may minimize the costs of renewable sources but artificially inflate network costs. Net cost modeling is challenging because it depends on the country's geography. But in principle, you can estimate costs per kilometer, with certain fixed amounts, and costs rise significantly for shorter distances. This is why we don't transmit short distances at once; spreading controllers over a long distance makes it more cost-effective. Brazil and China have similar DC connections, which are vital due to their size.

Laurens de Vries - Implementation

With the high capacity needed for interconnections, deciding whether to proceed is more challenging than incremental investment. It could be 16 separate projects built as needed. This development approach reduces risks. Optimal scale matters; when it's at its maximum, you can replicate the process several times and defer further processing. Phasing and planning can help manage risks and make it more appealing to investors. Focusing on key projects first and tendering or awarding them in sequence can be effective. Reducing competition for certain resources, like ships, can also lower costs. But there's always a risk, especially considering it involves multi-billion-dollar contracts, making it susceptible to corruption. A currency crisis in 1997 led to certain foreign loans not being repaid, causing significant damage to PLN's image. It's a reason for possible liberalization. PLN might reduce its role, stop building new plants, and leave that to market players who compete with each other. Then there are two models: a centralized system where PLN buys all the power, and a European-style model where large companies and distribution firms buy power directly, paying only for transmission. The part vulnerable to corruption would then be reduced to transmission alone, not production, as competition would govern production. There's also the issue of transitioning to a fully competitive model for small consumers, which is complex and has high transaction costs. An intermediate solution is letting utility companies become suppliers, which helps finance large wind projects. Less competition means better long-term planning but can also lead to inefficiencies and corruption. A compromise could be bundling at the utility company level, with large consumers and utility companies, creating a more manageable market.

Laurens de Vries - Market Structure

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