Mapping of Floating Solar PV Technical and Economic Potential in Indonesia

Thesis Project – Fauzan Maghdavi

Delft University of Technology - Master of Science in Sustainable Energy Technology

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Mapping of Floating Solar PV Technical and Economic Potential in Indonesia

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by

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Fauzan Maghdavi

Executive Summary

Indonesia has recently made a target to shift to more sustainable and renewable energy sources through its energy transition commitment to achieve net zero emissions by 2060. It is widely reported in various literature that the country has significant solar energy potential, yet only 211 MWp were installed until 2021. One of the forms of solar energy utilization can be floating solar PV, where the solar PV module is laid on the water's surface. At the moment of writing, the current solar PV in construction, potentially the largest in Indonesia, is the Cirata floating solar PV project with an installed capacity of 145 MWp. In addition, there are two additional floating solar projects that the memorandum signed between the developer and PLN, which are Saguling and Singkarak Lake, with a total capacity of 110 MWp. It shows an interesting development of floating solar in the country. Therefore, this research will enrich the knowledge of the potential deployment of floating solar since it may become one of the solutions to achieve the country's ambition of net zero emissions with the main research question:

"What is the technical and current economic potential of floating solar PV in Indonesia, and what schemes are required to increase its economic potential?"

This study uses QGIS as its main program for geospatial analysis in combination with the statistical program language to access the large and complex dataset. Maps of the water body's location, technical potential, and economic potential will be generated in QGIS and presented in this research.

The literature study shows a considerable knowledge gap in floating solar compared to ground-mounted solar. No available literature addresses the technical and economic potential of floating solar in Indonesia. In addition, an own site selection criteria need to be developed since the previous literature only briefly discussed the site selection criteria or did so without explaining why it becomes a limitation for selecting suitable water bodies. Therefore, this research aims to fill these gaps by providing a scientific contribution and becoming a valuable reference for the relevant stakeholders in Indonesia in shaping the energy transition strategies in the country.

Based on the site selection criteria of water occupancy, historical maximum wind speed, freshwater conditions, and protected lakes designation, Indonesia's total available water bodies are 16,322, with an area of up to 6,274 km2, including protected lakes. With a maximum of 5% water occupancy, the water body can have a floating solar on its surface for 307.5 km2 and can become up to 2,459.8 km2 if the water occupancy is increased to 40%.

This study shows that the technical potential of floating solar PV in Indonesia is 33 GWp at 5% water occupancy. There is still a way to increase the country's technical potential by increasing water occupancy with the potential installed capacity of up to 267 GWp at 40% water occupancy. However, this study finds that the economic potential of floating solar is significantly lower than its technical potential, with only 6.4 GWp at 5% water occupancy. Even though the water occupancy is increased to 40%, the economic potential installed capacity is only 45.7 GWp. This significant drop in potential is mainly due to the use of the economic attractiveness indicator by comparing the effective value of the levelized cost of electricity and the maximum electricity tariff in Indonesia, where a significant amount of water bodies have a result of levelized cost higher than the ceiling prices.

There are various support schemes to increase the economic potential of floating solar in Indonesia. Increasing water occupancy is an important scheme to increase the potential, followed by providing a capital costs incentive and feed-in tariff or increasing the ceiling tariff. However, the combination of schemes of water occupancy and capital costs subsidy is recommended to increase the economic potential. By increasing the water occupancy to 10%, the economic potential can be increased by 6 GWp

and can be even higher to 39 GWp if the water occupancy is increased to 40%. Meanwhile, the package of US$215 million for providing the capital cost subsidy is able to increase the economic potential by 2.8 GWp if the subsidy is targeted to provide an incentive in the amount of 10% value of the total capital expenditures.

Nevertheless, the FSPV can become an alternative solution to renewable energy sources for Indonesia's energy transition plan. This is clear from the technical potential of the FSPV in the country where the freshwater FSPV can meet significant electricity demand. However, the FSPV will only play significant role when support schemes are provided to boost the economic potential value of FSPV in the country.

A potential scenario is provided in this study to achieve the energy transition in Indonesia. The country requires to have investment in a 3 GW solar module production facility with a target operation date of 2026 if it would like to meet its target of 20 GWp installed capacity by 2030. In addition, the maximum of water occupancy must be increased to at least 10% in 2026 and an implementation of a capital incentive package from 2026 – 2028. If all conditions are met, Indonesia can reach a 20 GWp installed capacity of FSPV in 2030.

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Abbreviations

Abbreviation	Definition
ASCE	American Society of Civil Engineers
BOOT	Built Own Operate Transfer
BOS	Balance of System
BPP	Indonesia Electricity Tariff
BPS	Badan Pusat Statistik
CAPEX	Capital Expenditure
CFA	Central Finance Assistance
CTV	Crew Transfer Vessel
DHI	Diffuse Horizontal Irradiance
DNI	Direct Normal Irradiance
ESDM	Energi dan Sumber Daya Mineral
FSPV	Floating Solar PV
GHI	Global Horizontal Irradiance
GIS	Geographic Information System
GSA	Global Solar Atlas
GWA	Global Wind Atlas
HDPE	High Density Poly Ethylene
IEA	International Energy Agency
IEEFA	Institute for Energy Economics and Financial Analysis
IPCC	Intergovernmental Panel on Climate Change
IPP	Independent Power Producer
LCOE	Levelized Cost of Electricity
MOU	Memorandum of Understanding
OPEX	Operational Expenditures
OSM	Open Street Map
PLN	Perusahaan Listrik Negara
PV	Photovoltaic
QGIS	Quantum Geographic Information System
RUPTL	Rencana Usaha Penyediaan Tenaga Listrik
REC	Renewable Energy Certificate
SAM	System Advisor Model

Abbreviation	Definition
SDE	Stimulering Duurzame Energieproductie
SET	Sustainable Energy Technology
SOV	Service Operation Vessel
STC	Standard Test Conditions
VGF	Viability Gap Funding

1 Introduction

1.1 Indonesia Ambition on Energy Transition

The global energy situation and the earth's climate condition are shaking up countries in tackling climate change through an energy transition plan in ways no one can accurately predict. The IPCC 2021's climate report shows that the world can limit the global temperature rise only with an ambitious plan to cut emissions (IPCC, 2021). Most countries are making a continuous effort to meet their plan for the energy transition. As the fourth largest country population in the world, Indonesia has set its goal of achieving net zero emissions by 2060. It aims to have 85% of its energy supply from renewable sources. The country boasts a resource of renewable energy sources, with the most significant renewable energy potential coming from solar energy up to 208 GWp as stated in RUPTL 2021-2030, a document made by PLN, the country's state-owned electricity company (PLN, 2021). Another study by Langer et al. (2021) reviewed each type of renewable energy potential in Indonesia. The study shows that the penetration of solar PV in Indonesia is still low, albeit with a technical potential of 99 TWp. Meanwhile, a report from the Institute for Essential Services Reform provided another figure of technical potential for solar PV in Indonesia. The assessment shows the potential can be up to 20 TWp (IESR, 2021). Although there are discrepancies in the technical potential of solar PV in Indonesia, only 211 MWp were installed in the country until 2021, which is still far below the potential in all three references (Statista, 2022).

The current biggest solar PV in construction and potentially the largest installed solar PV in Indonesia is the Cirata floating solar PV project with an installed capacity of 145 MWp. A few other projects, such as Batam Solar Park with 2.2 GWp and Krakatau Steel with 40 MWp, plan to be developed, although the development is not clear enough to decide whether the project will continue or not (Fitch Solutions, 2021). In addition, a Memorandum of Understanding (MoU) was signed in 2022 for another two floating solar projects in Indonesia, Saguling and Singkarak Lake, with a total capacity of 110 MWp (PLN, 2022). The development shows Indonesia is interested in floating solar PV to achieve its renewable energy share. Moreover, the country also relied on hydropower as its third largest electricity source, behind coal and natural gas. One of the advantages of floating solar PV is to have a hybrid integration with a hydropower plant, as shown in the Cirata project, where it will be integrated with the Cirata hydropower plant. Therefore, it is possible for floating solar PV to become part of the solution for Indonesia's energy transition goal.

However, RUPTL 2021-2030 from PLN only mentioned 612 MWp of planned floating solar PV, mainly located on Java Island, the most condensed population in Indonesia (PLN, 2021). Moreover, a report by IEEFA in 2019 indicates several reasons solar energy investment is not moving in Indonesia, such as inconsistent policy implementation, cost competitiveness with fossil fuel energy, and local content requirements (Hamdi, 2019).

Indonesia's ambitious plan to achieve net-zero emissions by 2060 requires a commitment to reach its net-zero plan. Since the plan involves a combination of measures, including increasing the share of renewable energy in the country's energy mix with solar energy as the largest source of electricity generation, floating solar is likely to play an increasingly important role in achieving this goal.

1.2 Introduction to Floating Solar PV

Floating Solar PV (FSPV) is one type of solar PV based on installation location. Sahu et al. (2016) defined FSPV as a solar system installed in water bodies like oceans, lakes, lagoons, reservoirs, irrigation ponds, wastewater treatment plants, wineries, fish farms, dams, and canals. The definition from Sahu et al. (2016) suggested that as long as the solar module is placed in water bodies, the system can be considered as FSPV. Although the installation location is broad, the current FSPV installation is dominantly located on manmade water bodies (Spencer et al., 2018). Figure 1-1 from the floating solar handbook shows the schematic representation of the FSPV installation. The system has similar components as ground-based solar PV, such as a PV module, inverter, cabling, and combiner box. However, instead of having mounting frames as in ground-mounted PV, the FSPV has a mooring system and a pontoon as the floating structure.

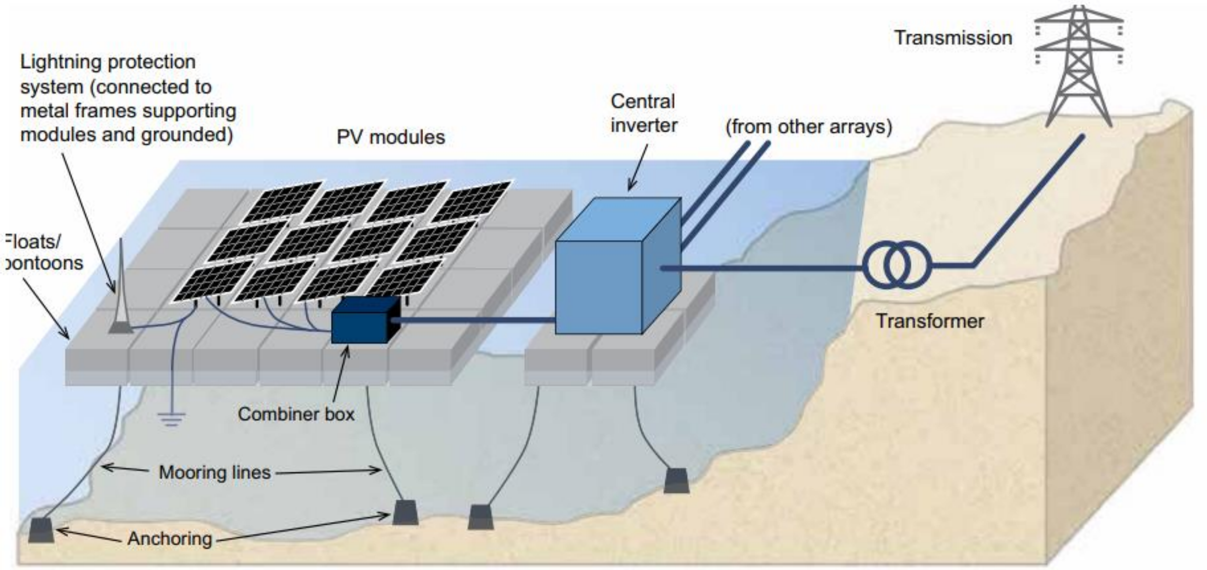

Figure 1-1 Floating Solar PV Schematic Representation (World Bank Group et al, 2019)

1.3 Research Objective

Two different contexts, which are technical and economic potential, will be assessed and analyzed for the research project. First, the study will assess the suitable location for FSPV installation. Second, technical potential assessment at a national level will be performed. Third, the economic potential will be observed using the LCOE method and compared with the current pricing mechanism in Indonesia. In addition, the thesis project will also analyze how to increase the economic potential of FSPV in Indonesia based on support schemes and policy analysis. The result of this project is to put a foundation in the technical and economic potential of floating solar PV at a national level as well as to provide a list of recommendations to increase floating solar PV penetration in Indonesia's energy mix. This research serves both project developer and Indonesian government to understand the potential of the FSPV in the country. A point of view of investment potential of FSPV in Indonesia is used together with the recommendations required to increase the investment of FSPV in Indonesia through a support schemes from the government.

1.4 Research Question

The main research question of this project is:

"What is the technical and current economic potential of floating solar PV in Indonesia, and what schemes are required to increase its economic potential?"

The research sub-question (SQ) is aimed to answer specific underlying elements in the main research question. Four research sub-questions are formulated:

SQ1: *"What is the total available and suitable area to install floating solar PV in Indonesia?"*

SQ2: *"What is the technical potential of floating solar PV in Indonesia?"*

SQ3: *"What is the current economic potential of floating solar PV in Indonesia?"*

SQ4: *"What are the current support schemes and regulations, and what support schemes can be recommended to increase the economic potential of floating solar PV in Indonesia?"*

1.5 Research Approach

The research combines quantitative and qualitative analysis to address the main project question. Cresswell (2017) identified this combination as mixed methods research since it involves collecting both quantitative and qualitative data, integrating the two forms of data, and using distinct designs that may involve philosophical assumptions and theoretical frameworks. This mixed approach concerns the nature of the main project question and sub-questions.

SQ1 will be answered through the observation and review of existing literature about the site selection and use that information to create own site selection criteria. The result will then be analyzed by creating a map of suitable water bodies using a Geographic Information System (GIS) to show the total available and suitable area of FSPV. It is then followed by technical potential calculation to answer SQ2. The calculation is performed through a combination of GIS and statistical programming language to produce a map of technical potential and calculate the annual electricity generation of each suitable water body.

As for SQ3, the economic potential is calculated using the LCOE method, and a map of the economic potential will be presented using GIS for further analysis. Finally, based on those findings, support schemes and policy proposals to increase the economic potential will be presented through quantitative analysis from the sensitivity method and observation of current support schemes and policies implemented in Indonesia and other countries.

1.6 Alignment to Sustainable Energy Technology Program

The research can be a foundation and useful reference in shaping the energy strategies of Indonesia, specifically in floating solar PV. The research also can be a comprehensive reference for the relevant stakeholders in the energy industry in Indonesia. On the other hand, the research topic is relevant to the SET program since this research deals with integrating solar and economic & society profiles. The academic contribution of this research also can fill in the identified gaps, which is the technical potential deployment of the FSPV map at a national level with the incorporation of economic potential and recommendations.

1.7 Thesis Outline

The proposal is structured as follows. In Chapter 2, a literature search and review will be performed to provide a foundation for developing this thesis project. Chapter 3 proposes the research approach and methodology to answer the main research question and sub-question. Next, in Chapter 4, site selection criteria and selected location will be shown. Chapter 5 shows the results of technical potential and will be followed by the economic potential in Chapter 6. Chapter 7 deals with how to increase economic potential through sensitivities, schemes, and policy analysis. Chapter 8 presents the discussion related to the results in the previous chapters. Then, Chapter 9 will propose recommendations for future research. Finally, Chapter 10 summarises the findings and answers the sub-questions and main research question.

The research flow diagram in Figure 1-2 presents the thesis outline of this thesis project.

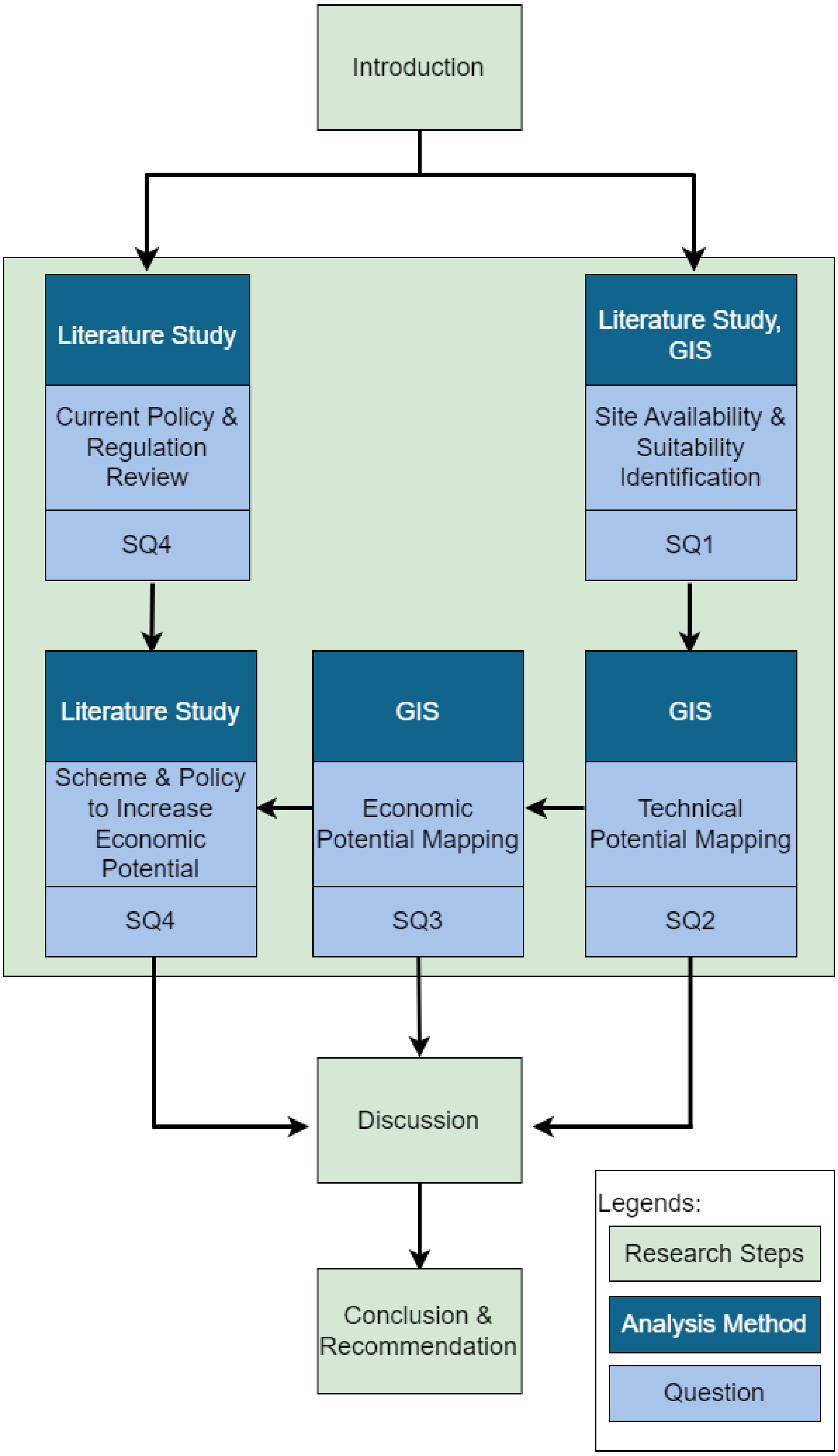

Figure 1-2 Thesis Outline

2 Literature Review

This section will conduct a literature review during the beginning of the thesis project to understand the state-of-the-art floating solar PV and its development in Indonesia. The literature search and review aims to understand the current state of knowledge on floating solar PV, identify gaps in the literature, and generate new insights or ideas for research. Furthermore, an overview of the key findings also will be given.

2.1 Literature Search

The literature search for the academic knowledge gap is focused on scientific articles and explored through Scopus and Google Scholar. However, books and professional literature such as reports will be used to strengthen the finding and explored through Google and TU Delft Online Library. The literature search will use keywords suitable to the thesis's main topic, which is floating solar PV in Indonesia. Table 2-1 shows the main keywords and synonyms that are used for the literature search.

Table 2-1 Main Keywords and Synonyms

Main Keywords	Synonyms
Floating	-
Solar	PV, Photovoltaic
Indonesia	Java, Sumatera, Kalimantan, Sulawesi, Papua, Bali
Potential	-
Economic	-
Policy	Regulation

Based on Table 2-1, a combination of keyword and synonyms are created for the search field. In addition, further filtering criteria is applied:

- Language : English and Bahasa Indonesia
- Publication Year : Starting from 2010
- Type of Publication : Journal Papers, Conference Proceedings, Reports, Books

Table 2-2 summarizes the keyword combinations and the results coming from the search for scientific articles. The search combinations are used within the article title, abstract, and keywords. The reviewed sample is the literature that is considered useful to build the thesis project based on the abstract scan.

Table 2-2 Summary of Literature Search and Result

Database	Search Combinations	Number of Search Results	Reviewed Sample
Scopus	(Solar OR PV OR Photovoltaic) AND Potential AND (Indonesia OR Java OR Sumatera OR Kalimantan OR Sulawesi OR Papua OR Bali)	411	8
Scopus	Floating AND (Solar OR PV OR Photovoltaic) AND Potential AND (Indonesia OR Java OR Sumatera OR Kalimantan OR Sulawesi OR Papua OR Bali)	11	6

Database	Search Combinations	Number of Search Results	Reviewed Sample
Scopus	(Solar OR PV OR Photovoltaic) AND Economic AND (Indonesia OR Java OR Sumatera OR Kalimantan OR Sulawesi OR Papua OR Bali)	245	7
Scopus	Floating AND (Solar OR PV OR Photovoltaic) AND Economic AND (Indonesia OR Java OR Sumatera OR Kalimantan OR Sulawesi OR Papua OR Bali)	13	3
Scopus	(Solar OR PV OR Photovoltaic) AND (Policy OR Regulation) AND (Indonesia OR Java OR Sumatera OR Kalimantan OR Sulawesi OR Papua OR Bali)	181	9
Scopus	Floating AND (Solar OR PV OR Photovoltaic) AND (Policy OR Regulation) AND (Indonesia OR Java OR Sumatera OR Kalimantan OR Sulawesi OR Papua OR Bali)	6	2
Google Scholar	Keywords: "Floating Solar", "PV", "Indonesia"	63	10
Google Scholar	Keywords: "Floating Solar", "PV", "Indonesia", 'Economic"	62	10
Google Scholar	Keywords: "Floating Solar", "PV", "Indonesia", "Policy"	58	7

Reviewed samples are the literature the author thoroughly reads to identify the knowledge gap and understand the state of the art of FSPV. There is literature with a "floating" keyword not reviewed due to the search results showing it with a "floating" word in its title or abstract. However, it is not necessarily mean the study is about FSPV. Therefore, several pieces of literature are omitted from the reviewed sample, such as in the case of only six reviewed samples out of 11 search results in one search combination.

The search results from Scopus also show that the research on floating solar PV in Indonesia is limited compared to the search combinations of solar PV in Indonesia without the "floating" keyword. Therefore, it is considered necessary to perform a literature review on a broader area outside of Indonesia to understand the development of floating solar. Table 2-3 shows the literature search and result of floating solar by omitting "Indonesia" as its keyword.

Table 2-3 Summary of Literature Search and Result – Without Indonesia Keyword

Database	Search Combinations	Number of Search Results	Reviewed Sample
Scopus	Floating AND (Solar OR PV OR Photovoltaic) AND Potential	592	10

2.2 Existing Literature Observation

In this section, the existing literature is reviewed. The literature is selected based on Table 2-2 and the abstract reading that may be helpful to build the thesis project. This literature is analyzed, and a knowledge gap identification will be performed to formulate the main research question.

2.2.1 Results and Findings

The selected literature is shown in Table 2-4 are considered as the primary literature to be as foundation of the study. However, it does not mean that the other reviewed sample are not used in the research. Table 2-4 presents the name of the authors, year of publication, title, and key insights from the literature.

Table 2-4 List of the Selected Literatures and Insights

Authors	Year	Title	Key Insights
Silalahi et al.	2021	Indonesia's Vast Solar Energy Potential	The publication assesses theoretical estimation potential of FSPV at national level through a GIS survey of area for freshwater surface with consideration of 5% of the reservoir surface that can be used for freshwater FSPV, and wind speed and wave for maritime FSPV
Damayanti et al.	2021	Development Area for Floating Solar Panel and Dam in the Former Mine Hole (Void) Samarinda City, East Kalimantan Province	Multi-criteria decision model is used to determine a suitable area for FSPV in specific location
Burke et al.	2019	Overcoming barriers to solar and wind energy adoption in two Asian giants: India and Indonesia	The study reviewed obstacles and barriers for solar energy penetration in Indonesia while comparing with India's effort to boost the solar energy in the country. The study also provides recommendations for boosting solar uptake in Indonesia based on identified barriers.
Aleluia et al.	2022	Accelerating a clean energy transition in Southeast Asia: Role of governments and public policy	The study reviewed the current status of Southeast countries to achieve the energy transition in regional context with a certain extent discussed about Indonesia progress
Sukarso & Kim	2020	Cooling Effect on the Floating Solar PV: Performance and Economic Analysis on the Case of West Java Province in Indonesia	Specific location for FSPV is studied based on technical potential and economic analysis
Ma'arif et al.	2020	Integration of Fisheries Technology with Solar PV Technology in Three Area of Indonesia	Specific location for FSPV is studied based on economic analysis through LCOE method
Lopes et al.	2022	Technical potential of floating photovoltaic systems on artificial water bodies in Brazil	Technical potential of FSPV is calculated by using QGIS and modified mathematical model

The first insight from the findings is that only one publication studied FSPV potential deployment at a national level in Indonesia (Silalahi et al., 2021). The publication used a GIS survey to estimate the lakes and reservoirs' surface area available in Indonesia. Based on the GIS survey, the publication identified the theoretical potential deployment of FSPV, considering the regulation of only up to 5% of the reservoir surface that can be used for FSPV. The other publication also provides a study on the potential deployment of FSPV in Indonesia although at a local level in freshwater conditions (Sukarso & Kim, 2020) and marine FSPV conditions (Ma'arif, Setiawan, & Pamitran, 2020). However, the study by Lopes et al. (2020) investigates the technical potential of FSPV in Brazil using GIS. The study also provided the site selection criteria and used a specific mathematical formula to calculate the electricity generation from FSPV.

The second insight is that only a publication from Damayanti et al. (2021) studied site suitability for FSPV at a detailed level in Indonesia. The publication is focused on a specific location in Kalimantan by investigating the suitable location of FSPV deployment in former mine holes with potential dam development. The study has several indicators to define whether the location is suitable for FSPV development, such as distance from the main road, distance from the power grid, and solar radiation. Meanwhile, the study from Silalahi et al. (2021) has considered site suitability in limited criteria which is based on wind speed and wave for maritime PV and regulation of up to 5% of the reservoir for freshwater FSPV.

The third insight is related to the economic analysis of FSPV application in Indonesia. Ma'arif et al. (2020) studied the economic competitiveness of FSPV with ground-mounted PV in three different locations. The assessment is based on LCOE and net present cost. Meanwhile, another study focused on economic analysis in West Java based on three methods (LCOE, IRR, and NPV) (Sukarso & Kim, 2020).

The fourth insight is no specific academic publication addressed the obstacles, barriers, or policy strategies for FSPV in Indonesia. However, there are considerable research papers that addressed it in a broader area which is solar energy. Burke et al. (2019) reviewed obstacles and barriers to solar energy penetration in Indonesia. The study also used India as the benchmark for solar energy deployment in Indonesia with recommendations for boosting solar uptake in Indonesia based on identified barriers and obstacles, such as avoiding the temptation to pursue national infant industry protection for the nascent solar manufacturing industry. Aleluia et al. (2022) provide the current status information of energy transition realization in the Southeast Asia region with a certain extent discussing Indonesia's progress in energy transition, such as the country's announcement that it could stop building new coal plants after 2023, which is considered as one of the key barriers in Burke et al. (2019) due to its entrenched market position.

The final insight from the literature review is about the research limitation and knowledge gaps on FSPV in Indonesia. As indicated by the result of applications from the search term in Scopus, FSPV-related research in Indonesia only holds less than 5% compared to the broader solar energy subject. Furthermore, Langer et al. (2021) studied that one of the main knowledge gaps for Indonesia to achieve its renewable energy potential is the limited work on renewable energy potential. However, if the literature review is extended to also include other locations outside Indonesia, there is literature that is considered useful as a reference to increase the understanding of the state of the art of FSPV.

2.2.2 Academic Knowledge Gap

The insights and findings from section 2.2.1 will be the foundation of knowledge gap identification. No academic articles address the potential deployment of FSPV based on specific suitable criteria at the national level in Indonesia. The only available source that indicates the theoretical potential of FSPV in Indonesia is from Silalahi et al. (2021), which does not elaborate on the data transparency to measure the potential of FSPV in the country. Therefore, this study will validate the result that is obtained in this research with the study from Silalahi et al. (2021). As for the economic assessment, there are also no available academic articles at a national level. However, several articles incorporated economic analysis at a local level. Hence, there are no academic publications that address the techno-economic assessment of FSPV at a national level. Moreover, there is no specific academic publication that addresses the obstacles, barriers, or development strategies for FSPV in Indonesia. Hence, the literature review needs to be expanded to other countries during the analysis and data collection, especially to the country that already has a relatively high deployment of FSPV as a matter of comparison. This thesis project targets to fill the knowledge gaps in Indonesia by providing a technical and economic potential deployment of the FSPV at a national level with the incorporation of how to increase the economic potential through support schemes and instruments.

3 Methodology

Since the answer from research sub-questions will be used to answer specific underlying elements in the main research question, therefore specific method will be selected for answering each research sub-questions. Section 3.1 will discuss the core concepts of this research. Next, Section 3.2 will present the methodology for answering SQ1. The methodology to calculate the technical potential and to answer SQ2 will be presented in Section 3.3. Then, the method to measure the economic potential of FSPV in Indonesia will be discussed in Section 3.4. Section 3.5 will discuss how to identify the recommended support schemes to increase economic potential. Finally, Section 3.6 shows the dataset used in this research.

3.1 Core Concepts

The core concept in this research is the basis that the author used to convey and answer the research questions. This concept is the foundation for the entire thesis, guiding the author's research methodology, analysis, and conclusions. For example, the study from Silalahi et al. (2021) defined the potential deployment in freshwater locations based on the area restriction of FSPV installation from Indonesia regulation, but the study does not show the calculation behind it and the meaning of the potential in the study. Therefore, the terms of potential shall be defined to maintain consistency in this project. In addition, this thesis used a geospatial analysis as its core concept to identify the patterns and trends of FSPV in Indonesia. A statistical programming language is used to process the large dataset used in this study for the data input in the geospatial program to support the geospatial analysis.

3.1.1 Definition of Potential

Blok & Nieuwlaar (2020) distinguish different types of potentials; theoretical, technical, economic, profitable, market, and policy-enhanced market potential. However, in this literature core concepts, only three types of potential will be used (theoretical, technical, and economical potential) as they were considered applicable to answer the research question and to define the FSPV development in Indonesia. A brief description from Blok & Nieuwlaar (2020) of the three types of potential is shown:

- Theoretical potential estimates the amount of renewable energy, in this case, solar energy, that can be generated by considering only the physical limits such as potential location.
- Technical potential estimates the energy assumed by considering practical constraints such as design limitations.
- Economic potential is part of the technical potential that analyses the economic attractiveness of renewable energy, such as using a discount rate and costs for FSPV to obtain the levelized cost of electricity.

The theoretical potential is used for estimating the potential FSPV deployment in Indonesia when only physical constraint is applied. The technical potential of the research project focus on the amount of installed capacity and annual electricity that can be generated in a particular water body. It is determined by various factors such as the available area, FSPV system arrangement, module efficiency, ambient temperature, wind speed, and solar irradiation. The economic potential of the research project focus on the ability of FSPV to generate electricity cost within the applicable ceiling price in Indonesia. Various factors, such as the cost of solar panels, floating systems, inverters, and the cost of installation, operation, and maintenance, determine it.

3.1.2 Geographic Information System and Statistical Programming

The map will be created using a Geographic Information System (GIS). This computer-based system provides data capture and preparation, management, manipulation, and analysis to produce a map (Huisman & By, 2009). QGIS software is used for the research project to present the map result of selected water bodies' technical and economic potential of FSPV in Indonesia. QGIS is used since it is allowed the author to use raster and vector layers datasets and present them in a map visualization. Two main tools from QGIS used in this study to support the geospatial analysis are *Zonal statistics* and *Distance to the nearest hub*. *Zonal statistics* is a statistical tool to obtain a certain value in this study, such as the maximum value, mean value, and sum of the values. Meanwhile, *Distance to the nearest hub* is a tool to measure the distance between two dataset's features.

Statistical programming language is used in this research to support the use of GIS in order to perform spatial data analysis. RStudio is used by the author since it is one of the known statistical programming languages and can handle large datasets. The statistical program merges the datasets and prepares the data for input in QGIS. In addition, it allows the author to perform repetitive tasks, for example, a calculation for each province in Indonesia, which saves time and reduces the risk of errors.

3.2 Site Availability and Suitability Identification

The site suitability assessment criteria will be built based on literature studies. The literature study shall mainly come from published scientific articles and books while reports from international bodies, government agencies, or private institutes may be used to support the factors identified. There is an example set of lists that need to be searched during this part:

- Physical constraints of suitable area
- Design criteria for the FSPV system that requires site information
- Assumptions to be used for site assessment
- Policy and/or regulations that may affect the site availability identification

Site selection in the research project indicates the practice of selecting suitable water bodies for the development of FSPV in Indonesia based on certain criteria. To select suitable water bodies, selection criteria used by existing works of literature will be reviewed to create the own selection criteria for the research project. Site selection is a critical step in FSPV development and deployment. Table 3-1 shows the summary of reviewed literature with the grouping based on similar characteristics to efficiently screen through each criterion.

Table 3-1 Water Bodies Selection Criteria Literatures Overview

Group	Criteria	Threshold	Location	References
Type of Water Bodies	Water Occupancy	5%	Indonesia	Silalahi et al. (2021)
			-	Deroo et al. (2021)
		10%	India	Kumar et al. (2021)
			Iran	Shayan & Hojati (2021)
		1 – 10%	Vietnam	Pouran et al. (2022b)
		5 -10%	India	Acharya & Devraj (2019)
		27%	United States	Spencer et al. (2018)
		1 – 100%	Chile	Haas et al. (2020)
	Water Purpose	Recreation, Fish and Wildlife Pond	Unites States	Spencer et al. (2018)

Group	Criteria	Threshold	Location	References
		Protected Area, Cultural Heritage, Military Activity	China	Guo et al. (2021)
	Water Conditions	Freshwater	United States	Spencer et al. (2018)
			Spain	Lopez et al. (2022)
			Switzerland	Eyring & Kittner (2022)
		Freshwater & Marine	Indonesia	Silalahi et al. (2021)
Climate Conditions	Maximum Wind Speed	15 m/s	Indonesia	Silalahi et al. (2021)
		10 m/s	Indonesia	Hendarti (2021)
Available Area	Minimum Surface Water	≥ 1,000 m^2	Switzerland	Eyring & Kittner (2022)
		≥ 4,000 m^2	United States	Spencer et al. (2018)
			India	Acharya & Devraj (2019)
			Turkey	Karipoğlu et al. (2022)
Water Level and Wave	Wave Height	4 m	Indonesia	Silalahi et al. (2021)
		2 m	United States	Spencer et al. (2021)
			-	Deroo et al. (2021)
	Water Depth	≥ 2 m	United States	Spencer et al. (2018)
		2 – 30 m	India	Acharya & Devraj (2019)
		≤ 50 m	-	Deroo et al. (2021)
		≤ 75 m	Indonesia	Hendarti (2021)
		≤ 80 m	India	Kumar et al. (2021)
Accessibility	Distance to Grid / Substation	≤ 1.5 km	Indonesia	Damayanti et al. (2021)
		≤ 3 km	-	World Bank Group et al. (2019)
		≤ 5 km	Vietnam	Nguyen et al. (2021)
		≤ 50 km	Turkey	Karipoğlu et al. (2022)
		≤ 80 km	United States	Spencer et al. (2018)
	Distance to Road	≤ 0.25 km	China	Guo et al. (2021)
		≤ 1 km	Indonesia	Damayanti et al. (2021)
		≤ 10 km	Vietnam	Nguyen et al. (2021)
		≤ 50 km	Turkey	Karipoğlu et al. (2022)
Solar Resources	GHI	≥ 1,550 kWh / m^2	Turkey	Karipoğlu et al. (2022)
		≥ 1,700 kWh / m^2	Indonesia	Damayanti et al. (2021)
		≥ 1,800 kWh / m^2	India	Kumar et al. (2021)
		≥ 1,825 kWh / m^2	Vietnam	Nguyen et al. (2021)

Additionally, a review of the existing regulations in Indonesia is performed to gain additional information on whether some regulations may have specific criteria for the development of FSPV before reviewing each group's criteria in Table 3-1. Table 3-2 shows the regulations and its remarks.

Table 3-2 Regulations Review List

Details	Reference
Water Occupancy	PERMENPUPR No.27/PRT/M/2015
National Priority Lake	PP No.60/2021

Based on the review of each criterion in Table 3-1 and with the considerations from the existing regulations listed in Table 3-2, water bodies selection criteria will be created for the research in Chapter 4. Depending on the criteria, specific secondary data collection such as water body location, solar irradiation, and weather data from publicly available datasets are required to become an input for creating a map of suitable water bodies location of FSPV in Indonesia. Additionally, the theoretical potential of FSPV will be reviewed based on the use of the only physical constraint.

3.3 Technical Potential Calculation and Mapping

Technical potential in this study refers to the average annual energy production of FSPV and the potential installed capacity of FSPV in Indonesia with consideration of specific technical information and limitation such as module efficiency, module size, floating system arrangement, solar resource, and available area. The annual energy production from FSPV and its installed capacity will be calculated and mapped into the selected location using GIS-based software in QGIS. The map output will be the location of FSPV deployment with color and size differentiation based on the potential installed capacity.

3.3.1 Main Equipment of FSPV

PV module and floating system selection are pivotal to calculating technical potential since they will affect the total installed capacity of FSPV and annual energy production. First, the PV module is selected based on the consideration that it should be available in Indonesia and able to meet its local content requirement (Hamdi, 2019). Canadian Solar is selected for this research since it has a production facility in Indonesia while also having a worldwide presence (Canadian Solar, n.d.; Osborne, 2013). Table 3-3 shows the selected PV module datasheet.

As for the floating system, the list of system suppliers that is capable of large-scale production is fewer than the PV modules supplier (World Bank Group et al., 2019). There are 11 floating system suppliers listed as capable of large-scale FSPV systems, with only four floating system suppliers with more than 100 MWp installed capacity in the report. Meanwhile, HDPE floats technology is the most common type of technology used for floating systems, although there are other types of technology, such as using pontoon with metallic structures and membranes. Ziar (2021) briefly introduces the advantages and disadvantages of these technologies. HDPE floats have the lowest cost compared to the other technologies, although it is vulnerable to high wind speed. Meanwhile, pontoon with metallic structures allows the system to have axis tracking but at a higher cost. As for the membranes, it is suitable for offshore applications, but with the highest capital cost, operational cost, and modules cannot be tilted. Sungrow with HDPE floats is selected for this research since Indonesia is known as a low wind speed region and to achieve the lowest possible cost to obtain a higher economic potential. Moreover, another study by Lopes et al. (2020) and Pouran et al. (2022b) also use HDPE floats, thus becoming another basis for the selection. In addition, the supplier has the largest installed capacity for floating systems in the world while also having a presence in Southeast Asia (World Bank Group et al., 2019).

Table 3-3 PV Module Datasheet

Parameter	Description / Value
Panel	Canadian Solar Panel HiKu 450
Nominal Max. Power	450 Wp
Dimensions	2108 x 1048 x 40 mm
Open Circuit Voltage (V_{oc}) at STC	40.5 V
Short Circuit Current (I_{sc}) at STC	11.12 A
Efficiency at STC	20.37 %
Temperature Coefficient (P_{max})	-0.35 % / °C
Temperature Coefficient (V_{oc})	-0.27 % / °C
Temperature Coefficient (I_{sc})	-0.05 % / °C
Module Reference	(Canadian Solar, n.d.)

3.3.2 Effective Area and Area Occupancy

Two terms are used in the project related to the calculation of area. First, *Effective Area* is a definition for the area occupied by the PV module with the value depending on the total installed capacity of FSPV and module size. The effective area value will be used for calculating the technical potential annual energy production. Second, *Area Occupancy* is a definition for FSPV system occupancy in certain water bodies. Since the FSPV system consists not only of PV modules but also the floating system and inverter, the area required for FSPV system deployment also depends on the quantity and dimensions of other components, which leads to the Area Occupancy required being larger than the Effective Area.

Lopes et al. (2020) and Pouran et al. (2022b) developed a model for calculating effective area and area occupancy in FSPV, which considered the dimensions of the PV module and the floating system. Both works of literature used different types of modules while having similar floating suppliers and floating system configurations from Sungrow. The calculation of effective area and area occupancy in this research project follows a similar approach used in both studies. Lopes et al. (2020) and Pouran et al. (2022b) used a single-row configuration with its schematic model shown in Figure 3-1. However, the FSPV configuration used in this research will be different from the referred studies.

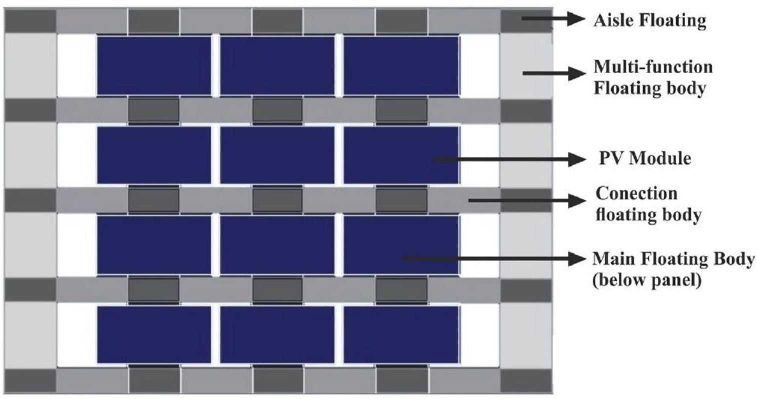

Figure 3-1 FSPV Configuration in Literatures (Lopes et al., 2020; Pouran et al., 2022b)

Single-row configuration is one of the possibilities in FSPV system arrangement. It has advantages in maximizing operation and maintenance comfort as each module can be accessed from two sides of the pathway. For example, there are other possible arrangements using 2-in-a-row or 4-in-a-row configurations as marketed by floating system suppliers. A double-row configuration will maintain its operation and maintenance comfort as it can access each module from a pathway while increasing the effective area in a similar size of area occupancy compared to a single-row configuration. Meanwhile, a 4-in-a-row configuration is capable of increasing the effective area more than double row configuration, thus leading to a higher installed capacity; however, with the expense of potential issues that may arise during the operational period, such as for module cleaning process and module repair that is not accessible from floating aisle. Therefore, for the rest of the technical potential calculation, the double-row configuration is selected to keep the operational comfort while increasing the effective area compared to the arrangement used in Lopes et al. (2020) and Pouran et al. (2022b). The Double Row schematic configuration used for the research project is shown in Figure 3-2.

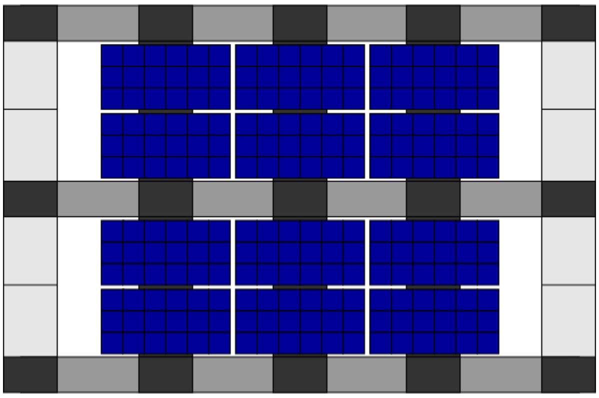

Figure 3-2 FSPV Configuration in Double Row Configuration (Own Illustration)

To measure the effective area based on the available area occupancy, the formula from Pouran et al. (2022b) is adopted as shown in equations 1-2. Although the literature uses different configurations, the approach to arrive at the effective area would still be the same.

$$P_{FSPV} = \frac{A_{RES} \times \%C_{RES}}{A_{1MWp}} \times 1\ MWp \qquad (1)$$

$$A_{eff} = \frac{P_{FSPV}}{P_M \times 10^6} \times A_M \qquad (2)$$

Where:

P_{FSPV} : Installed capacity (MWp)
A_{RES} : Total water bodies area (m^2)
A_{1MWp} : Total area occupancy per 1 MWp (m^2)
A_{eff} : Total effective area (m^2)
$\%C_{RES}$: Percentage water occupancy (%)
P_M : Nominal module power (Wp) – 450 Wp
A_M : Module area dimension (m^2) – 2.209 m^2

The value of A_{1MWp} is used as a factor for calculating the technical potential capacity of FSPV in certain water bodies with different maximum water occupancy. The value consists of the dimension of each type of floating body, PV module, and inverter support as shown in equation 3. The dimension used for the floating body and inverter support is retrieved from Sungrow (n.d.) with Table 3-4 shows the summary of the dimensions.

$$A_{1MWp} = MF^* + CF + AF + MFF + PV + I \quad (3)$$

Table 3-4 FSPV System Dimension Summary per 1 MWp

Item	Function	Dimension	Area (m^2)	Quantity per 1 MW	Area per 1 MW
Main Floating Body [MF*]	Support PV modules	1110 x 880 mm	0.9768	2,220	2,168 m^2
Connection Floating Body [CF]	Connection of support floats	1212 x 410 mm	0.49692	4,588	2,280 m^2
Aisle Floating Body [AF]	O&M pathway	880 x 410 mm	0.3608	4,619	1,666 m^2
Multi-Function Floating Body [MFF]	Cable support and electrical connections	1110 x 880 mm	0.9768	120	117 m^2
PV Panel [PV]	Modules	2108 x 1048 mm	2.209	2,220	4,903 m^2
Inverter Support [I]	Inverter support	4003 x 2470 mm	9.887	1	9,9 m^2

The main floating body area calculated for A_{1MWp} only considered the occupied space between modules and the aisle floating body as the main floating body is used as a support of PV modules and is located under the PV panel. This occupied space accounts for 413.1 m^2 for every 1 MW. A schematic figure of the main floating body and PV panel is shown in Figure 3-3 to help the understanding of the concept of occupied space.

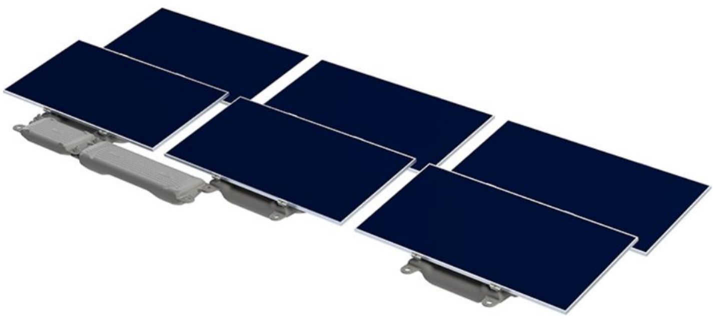

Figure 3-3 3-D Schematic Figure of Main Floating Body, PV Module, and Aisle Floating Body (Ciel et Terre, n.d.)

Therefore, by using the information in Table 3 and calculated using equation 3, in every 1 MWp FSPV system an area of 9,389 m^2 is required to cover the area requirements of the PV module and the floating system. The value then will be used to determine the technical potential installed capacity in Indonesia as well as for calculating its annual energy generation.

3.3.3 Performance Ratio and Electricity Generation

Performance Ratio (PR) is the overall efficiency of a solar PV system, which is calculated by dividing the actual energy output of the system by the theoretical maximum energy output from the PV system. The PR value used for the research project ranges from 78.8 to 82.5% for tropical climates (World Bank Group et al., 2019). The range value is used due to the nature of actual energy output from the FSPV system and may vary according to the location, selection of equipment, soling, and shading losses. The highest floating solar PV performance ratio value is identified in a temperate climate between 89.3 to 93.5% (World Bank Group et al., 2019). The PR value will then be used to calculate the technical potential annual electricity generation.

There are three different methods used to determine the annual electricity production in the research project, and all of them used the same value of performance ratio and effective area:

1. Simple;
2. FSPV Modified; and
3. Time series.

The results obtained from each method will then be analyzed and compared. Three different approaches in calculating technical potential are used to better understand the electricity generation from floating solar. This is mainly because of the expectation that the floating solar system has better module efficiency than ground-mounted solar PV. A study by Lopes et al. (2022) used a mathematical model for floating solar and compared it with the actual generation. The result shows that the mathematical model well represents the actual generation. This mathematical model will be represented in the FSPV Modified method. Another study by Pouran et al. (2022b) applied an assumption of a 10% higher module efficiency of floating solar by using a model for ground-mounted solar PV. However, it indicates that the increased efficiency may vary from 0.79% to 15.5%. The time-series method represents the use of a typical land-based model formula and will later be compared with the FSPV Modified method. Another study from Sukarso & Kim (2020) will also validate the results since the study investigated the cooling effects of FSPV on module efficiency and compared it with ground-mounted solar PV. The study is located in the Cirata reservoir in Indonesia, thus having a good representation for a validity check.

3.3.4 Simple Method

The Simple method is the simplest method compared to the other method since it does not require complex weather data such as wind speed and ambient temperature as an input, hence only required the module efficiency at Standard Test Conditions (STC) to determine its module efficiency.

$$E_{FSPV} = A_{eff} \times \eta_{STC} \times G_{GTI} \times PR \tag{1}$$

Where:

E_{FSPV} : Annual energy production (kWh/year)
A_{eff} : Total effective area (m^2)
η_{STC} : Module efficiency in STC (%)
G_{GTI} : Annual solar irradiance at optimum tilt (kWh/m^2 per year)
PR : Performance Ratio (ratio of AC system efficiency and DC module efficiency)

The formula calculates the amount of electricity that can be generated by FSPV given its effective area, module efficiency, the annual solar irradiation it receives, and its performance ratio.

3.3.5 FSPV Modified Method

The FSPV Modified method is a calculation method to measure the annual electricity generation from FSPV with consideration of average wind speed and ambient temperature. The formula for the FSPV Modified method is adopted from a specific mathematical model for FSPV by Lopes et al. (2022) and shown in Equations 2 – 4.

$$E_{FSPV} = A_{eff} \times \eta_{C} \times G_{GTI} \times 365\ x\ PR \tag{2}$$

$$\eta_C = \eta_{STC}(1 - \beta_{ref} (T_c - T_{ref}) \quad (3)$$

$$T_c = T_{avg} + w \left(\frac{0.32}{8.91+2V}\right) G_{GTI} \quad (4)$$

Where:

E_{FSPV}	: Annual energy production (kWh/year)
A_{eff}	: Total effective area (m^2)
η_c	: Average annual solar PV module adjusted efficiency (%)
η_{STC}	: Module efficiency in STC (%)
β_{ref}	: Coefficient of correction of efficiency maximum power ($^oC^{-1}$)
T_C	: Average daily module operating temperature (^oC)
T_{ref}	: STC temperature (^oC)
T_{avg}	: Average daily ambient temperature (^oC)
w	: Mounting coefficient; floating solar is considered 1.0
V	: Average daily wind speed (m s^{-1})
G_{GTI}	: Daily solar irradiance at optimum tilt (kWh/m^2 per day)
PR	: Performance Ratio (ratio of AC system efficiency and DC module efficiency)

The FSPV Modified method requires more datasets compared to Simple Method in its formula calculation. The wind speed, daily ambient temperature, and daily solar irradiance will affect the module temperature and subsequently its efficiency as shown in Equations 3 and 4.

3.3.6 Time-Series Method

The Time-Series method is the most detailed approach compared to the other methods. The Time-Series method required hourly time-series datasets of the wind speed and ambient temperature used to calculate the module temperature. Moreover, instead of using secondary datasets of solar irradiance at an optimum tilt, the total irradiation value is derived from a different input of solar irradiance as shown in Equations 5-8 (Smets, et al., 2016).

$$G_M^{Dir} = DNI \times \cos(AOI) \times SF \quad (5)$$

$$G_M^{Dif} = DHI \times SVF \quad (6)$$

$$G_M^{ground} = GHI \times \propto \times (1 - SVF) \quad (7)$$

$$G_M = G_M^{Dir} + G_M^{Dif} + G_M^{ground} \quad (8)$$

Where:

G_M	: Total irradiance on the module (W /m^2)
G_M^{Dir}	: Direct irradiance on the module (W /m^2)
G_M^{Dif}	: Diffuse irradiance on the module (W /m^2)
G_M^{ground}	: Ground reflected irradiance on the module (W /m^2)
DNI	: Direct Normal Irradiance (W /m^2)
DHI	: Diffuse Horizontal Irradiance (W /m^2)
GHI	: Global Horizontal Irradiance (W /m^2)
AOI	: Angle of Incidence (-)
SVF	: Sky View Factor (-)
SF	: Shading factor (-)

Since the FSPV is located in water and considered a relatively flat surface, thus a shading effect is expected to be minimal (World Bank Group et al., 2019). The shading factor requires a field measurement to check whether a possible obstruction may cast shade into the system. Therefore, the shading factor is not calculated in detail for each water body. However, this is being compensated by using assumptions of Performance Ratio from World Bank Group et al. (2019), which already considered the shading losses in its value.

The obtained result of total irradiance on the module will be used as an input for determining the operating module efficiency. Equations 9-14 shows the step to obtain hourly operating module efficiency (Smets et al., 2016). Equation 13 is a formula to determine the hourly module temperature by using Sandia Temperature Model (Sandia, n.d.).

$$V_{OC}(25^{o}C\,,G_M) = V_{OC}(STC) + \frac{nk_BT_{STC}}{q} ln\left(\frac{G_M}{G_{STC}}\right)N \quad (9)$$

$$I_{SC}(25^{o}C\,,G_M) = I_{SC}(STC)\left(\frac{G_M}{G_{STC}}\right) \quad (10)$$

$$P_{MPP}(25^{o}C\,,G_M) = FF \times V_{OC}(25^{o}C\,,G_M) \times I_{SC}(25^{o}C\,,G_M) \quad (11)$$

$$\eta(25^{o}C\,,G_M) = \frac{P_{MPP}(25^{o}C\,,G_M)}{A_M \times G_M} \quad (12)$$

$$T_M = G_M \times exp^{a+b\times WS} + T_{amb} \quad (13)$$

$$\eta(T_M\,,G_M) = \eta(25^{o}C\,,G_M) \times (1 + k(T_M - T_{STC})) \quad (14)$$

Where:

$V_{OC}(25^{o}C\,,G_M)$	: Open circuit voltage at STC temperature and variable irradiance (V)
$V_{OC}(STC)$	: Open circuit voltage at STC conditions (V)
n	: Ideality factor (-)
k_B	: Boltzmann constant (J/K)
T_{STC}	: STC temperature (°C)
q	: Elementary charge (C)
G_M	: Total irradiance on the module – variable (W /m^2)
G_{STC}	: Total irradiance on the module at STC conditions (W /m^2)
$I_{SC}(25^{o}C\,,G_M)$	: Short circuit current at STC temperature and variable irradiance (A)
$I_{SC}(STC)$	: Short circuit current at STC conditions (A)
$P_{MPP}(25^{o}C\,,G_M)$	: Power output module at STC temperature and variable irradiance (W)
FF	: Fill Factor (-)
A_M	: Module area dimension (m^2)
T_M	: Operating module temperature (°C)
a	: Solar module mounting parameter (-)
b	: Solar module mounting parameter (-)
WS	: Wind speed (m/s)
T_{amb}	: Ambient temperature (°C)
$\eta(T_M\,,G_M)$	: Operating module efficiency (%)
k	: Coefficient of correction for efficiency (°C^{-1})

The operating module efficiency and total irradiance will be as input for calculating the hourly electricity production as shown in Equation 15.

$$E_{FSPV} = A_{eff} \times \eta(T_M, G_M) \times G_M \times PR \tag{15}$$

The Time-Series Method will be applied to only several selected water bodies. Table 3-5 shows the selected water bodies and the description of their selection. The result from selected water bodies in the Time-Series method then will be compared with the other method.

Table 3-5 Water Bodies for Time-Series Method

No.	Water Bodies	Description
1	Singkarak Lake	Representing Sumatera, Protected Lake, Lake with Hydro Plant, Listed in National Electricity Plan
2	Wonorejo Reservoir	Representing Java, Reservoir with Hydro Plant, and Listed in National Electricity Plan
3	Sentani Lake	Representing Papua, Protected Lake, and Lake with Hydro Plant
4	Manggar Reservoir	Representing Kalimantan and Reservoir for Irrigation
5	Towuti Lake	Representing Sulawesi, Non-Protected Lake, and Lake with Hydro Plant
6	Patamawai Lake	Representing province with large annual irradiation, Non-Protected Lake
7	Cirata Reservoir	Comparison with previous study, Reservoir with Hydro Plant

3.4 Economic Potential Calculation and Mapping

The economic potential will be analysed based on the results from the technical potential. LCOE will be the method used to calculate the economic potential in which electricity production relies on the result of the technical potential. Levelized cost of electricity (LCOE) is a figure to define the cost of generating one-kilowatt hour (kWh) of electricity produced by a power generation facility over the lifetime (Smets et al., 2016). The formula to calculate the LCOE is shown in Equation 16.

$$LCOE = \frac{C_0 + \sum_{t=1}^{n} \frac{C_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}} \tag{16}$$

Where:

C_o = Investment expenditure in year 0
C_t = Operational and maintenance expenditures in year t; inflated every year
F_t = Fuel expenditures; F_t is 0 for PV
E_t = Electricity production in year t
r = Discount rate; nominal values for this research
n = Operational period of FSPV project

The LCOE takes into account the costs associated with a system, including installation, operation, maintenance, and fuel; for solar PV, the fuel is zero. Since there will be no fuel expenditures for solar power plants, the major cost will come from the investment expenditure or capital expenditure (CAPEX) such as PV module, floating system, inverter, and balance of the system. The LCOE for FSPV may vary depending on the location and the investment required for the system.

The Operational Expenditures (OPEX) are accounted for in the LCOE calculation to show the cost of operation of the FSPV plant after the commercial operation. As the cost component of OPEX in the FSPV is consist of operational services such as manpower, maintenance of panels, and insurance as listed in World Bank Group et al. (2019), the OPEX component is inflated every year with a certain value of inflation rate. The inflation rate is used to define the increase of the OPEX in the FSPV plant.

Meanwhile, the use of discount rate is used to discount the future value of cost and revenue (cash flow) into its present value. However, two terms of rate are used for the discounting namely real discount rate and nominal discount rate. Darling et al., (2011) described the real discount rate as a rate that is not including inflation while a nominal rate includes inflation. The use of real or nominal depends on the purpose of the rate, where a real discount rate is typically used by the government to show the real changes in a certain economic sector. Meanwhile, the nominal discount rate is commonly used by private entities to represent financial uncertainty in the future by considering inflation. For example, the nominal discount rate is used when a private entity needs to borrow money from the bank for an investment in a project. Since, the approach of this research used a view from a project developer, therefore a nominal discount rate is used.

3.4.1 Ceiling Price Indicator

The LCOE calculation result will be compared with the latest applicable ceiling price in Indonesia based on PP No. 112/2022. The ceiling price in the latest regulation in Indonesia applies a different ceiling price based on capacity and contract year, as shown in Table 3-6. The ceiling price is the cost of power generation or the maximum electricity purchase tariff in Indonesia and is used as a reference for power project development.

Table 3-6 Ceiling Price

Capacity	Ceiling Price (cent USD / kWh)	
	Year 1 to 10	Year 11 to (Max. 30)
<1 MW	10.8965 x F	6.536
1 to 3 MW	9.443 x F	5.6715
3 to 5 MW	8.3315 x F	4.997
5 to 10 MW	7.847 x F	4.712
10 to 20 MW	7.543 x F	4.522
>20 MW	6.6025 x F	3.9615

Where F is the location factor multiplier based on the location where the potential project is located. Table 3-7 shows the location factor based on the regulation.

Table 3-7 Location Factor for Ceiling Price

F Value	Location
1.00	Jawa, Madura, Bali
1,10	Sumatera, Kalimantan, Sulawesi, Bangka Belitung, Small Islands in Jawa, Madura, Bali
1,15	Small Islands in Sumatera, Kalimantan, Sulawesi
1.20	Kep. Riau, Nusa Tenggara, Mentawai

F Value	Location
1.25	Maluku, Maluku Utara, Small Islands in Nusa Tenggara
1.30	Small Islands in Maluku, Maluku Utara
1.50	Papua, Papua Barat

There are two conditions for the relation between LCOE and electricity ceiling price as below:

- If LCOE > ceiling prices: Not Economic Potential
- If LCOE ≤ ceiling prices: Economic Potential

Both ceiling prices on Year 1 to 10 and from Year 11 are considered in the economic potential indicator. The electricity prices of FSPV needs to be equal or under the ceiling prices in order to be included in the economic potential.

The map output from QGIS will be the location of FSPV deployment with color differentiation based on the economic potential deployment of FSPV in Indonesia to demonstrate which location the FSPV is economically attractive.

3.4.2 LCOE Cost Components of Floating Solar PV Plants

According to the LCOE formula in Equation 16, the cost component of FSPV can be divided into two categories: capital costs and operating costs. The floating solar handbook by World Bank Group et al. (2019) defined the component for capital costs and the operating costs for FSPV. Capital costs include the cost of the solar PV modules, inverters, floating systems, and Balance of System (BOS), design, and construction. On the other hand, operating costs include maintenance, monitoring, and repair costs, as well as the cost of insurance and financing. The capital costs of floating solar PV systems are higher than those of ground-mounted solar PV systems, as shown in the handbook, due to the additional materials and labor required for the floating systems, BOS, and construction. In order to determine the value used as an input for the LCOE, a comparison of several studies is reviewed with the summary of the comparison shown in Tables 3-8 and 3-9.

Table 3-8 Capital Cost Comparison

Item	Unit	References						
		Sungrow	Radiant Energy	Rosa-Clot & Tina	Pinto & Stokkermans	CECP	World Bank, ESMAP, & SERIS	Sukarso & Kim
		2018	2023	2020	2020	2022	2019	2020
		-	Indonesia	-	UK	India	-	Indonesia
Modules	$ / Wp		0.19 – 0.21	0.25	0.22	0.33	0.25	0.25
Inverters	$ / Wp			0.12	0.1	0.03	0.06	0.1
Floating System	$ / Wp	0.21		0.14 – 0.18	0.15 – 0.23	0.19	0.15	0.15
BOS	$ / Wp				0.23	0.10	0.13	0.13
Design, Construction , T&C	$ / Wp			0.08	0.31	0.10	0.14	0.14

Item	Unit	References						
		Sungrow	Radiant Energy	Rosa-Clot & Tina	Pinto & Stokkermans	CECP	World Bank, ESMAP, & SERIS	Sukarso & Kim
		2018	2023	2020	2020	2022	2019	2020
		-	Indonesia	-	UK	India	-	Indonesia
Contract & Environment Studies	$ / Wp				0.23	0.01		0.01

Table 3-9 Other LCOE Cost Element Comparison

Item	Unit	References			
		CECP	World Bank, ESMAP, SERIS	Sukarso & Kim	BRIN
		2022	2019	2020	2022
		India	-	Indonesia	Indonesia
Operating Costs	%	1.5	1.5	2	
Years of Operation	Year	25	20	25	
Inflation Rate	%	4	2	3.131	3.25 – 3.75
Discount Rate (WACC)	%	8.28	6 - 10	10	
Module Degradation Rate	%	0.55	1	0.5	

In addition to the capital and operating costs of the solar PV components, the cost of transmission lines and access roads must also be considered for the research project for the additional cost of the investment expenditure in year 0. The transmission line cost component can be a factor in defining the economic potential, especially when the project is located far from the existing substation or grid. Additionally, the cost of the access road to the floating solar PV site must also be considered as it will determine the accessibility of the project, for example, for delivery of equipment during the operational period.

The transmission line cost is extracted from ETSAP (2014) and converted into a range value of 847 – 3,769 US$(2021)/MW/km. The median value of 2,308 US$/MW/km is used for the cost function input of the transmission line. Meanwhile, the cost of the access road is based on the market price in Indonesia with the assumption of using 6 meters wide road and type K250+B0 (Indosarana Gemilang, n.d.). The cost function for the access road used in the research project is 1,950,000 IDR/m or equal to 126 US$/m.

The distance of the transmission line and the access road from the water body is measured using a tool function in QGIS, Distance to the nearest hub. The tool will establish a straight line from the water bodies to the nearest transmission line and road hub. The hub for the point of reference in the transmission line is a substation or grid connection point. Meanwhile, the hub for point of reference in the road is the road network in Indonesia.

Based on several pieces of literature, a cost function for each component is developed mainly based on the median value or cost function from Indonesian located literature. Table 3-10 shows the cost function used for economic potential calculation in the research project.

Table 3-10 Cost Function for Economic Potential

Item	Unit	Value
Modules	$/ Wp	0.21
Inverters	$/ Wp	0.08
Floating System	$/ Wp	0.19
Balance of System	$/ Wp	0.13
Design, Construction, Testing, & Commissioning	$/ Wp	0.14
Contracts, Permit, and Environment Studies	$/ Wp	0.01
Road	$/ m	126
Transmission Line	$/ MW / Km	2,308
Annual OPEX	%	2
Years of Operation	Year	25
Inflation Rate for OPEX	%	3.5
Discount Rate - Nominal	%	8
Module Degradation Rate	%	0.75

3.5 Sensitivity Analysis, Scheme, and Policy to Increase Economic Potential

First, sensitivities analysis will be applied to the cost component for LCOE calculation such as capital expenditure, operation & maintenance, and discount rate. Another sensitivity analysis is performed on the changes in ceiling price and potential learning curve on FSPV. The sensitivity result with the maximum water occupancy of 5% will be used to identify which support mechanism that could significantly increase the economic potential in Indonesia. Table 3-11 summarize the sensitivity analysis for the research project.

Table 3-11 Sensitivity Analysis Scenarios

	Scenarios
FSPV System Costing	+/- 10% of Capital Expenditures (Modules, Inverters, EPC, BOS)
	+/- 10% of Operational Expenditures
	+/- 10% Discount Rate
Others	+10% Ceiling Price Year 1 to 10 & Year 11 to 25
	+10% Ceiling Price Year 1 to 10
	+10% Ceiling Price Year 11 to 25
	Estimated Cost of FSPV System in 2030 (use projected capital costs in 2030 from CSIRO (2022) – Base Ceiling Price

Current energy policies and regulations in Indonesia will be reviewed to identify schemes that have already been implemented in Indonesia. Support schemes and policy implementation analysis of other countries are also required to increase the reference in a wider context. Based on the identified current scheme and policy available, and the result of economic potential, a set of recommendations of schemes and policy will be given to increase the economic potential with a prioritization of the recommended items.

3.6 Datasets Summary for GIS

Table 3-12 summarise the secondary datasets that are used for the input of GIS.

Table 3-12 Datasets Summary

Data	Descriptions	
Water Bodies, Substation, Road Network	Source	OpenStreetMap
	Spatial range	Indonesia
	Spatial resolution	Approximately 1 m
	Data type	Vector
	Time period	2022
Weather Data: - 2m temperature - 10m u-wind - 10m v-wind	Source	ERA5 hourly data on single levels from 1959 to present
	Spatial range	Indonesia
	Spatial resolution	250m x 250m
	Data type	Raster
	Time period	2002 – 2021
Global irradiation at optimum tilt & Temperature	Source	Global Solar Atlas
	Spatial range	Indonesia
	Spatial resolution	250m x 250m
	Data type	Raster
	Time period	2007 – 2018
Time-Series Solar Irradiance: - GHI - DNI - DHI - Solar azimuth - Albedo	Source	NSRDB – NREL
	Spatial range	Indonesia
	Spatial resolution	2km x 2km
	Data type	Raster
	Time period	2018
Average wind speed – 10m	Source	Global Wind Atlas
	Spatial range	Indonesia
	Spatial resolution	250m x 250m
	Data type	Raster
	Time period	2007 – 2018

Bias correction is used to reduce biases in a data set. These biases can arise from various sources, such as different input data (satellite and atmospheric) and low spatial resolution. If left uncorrected, these biases can lead to inaccurate or misleading results in data analysis. Bias correction techniques involve adjusting the data set by applying statistical methods to remove or reduce the effects of bias. Langer et al. (2022) applied a bias correction to its ERA-5 wind data with the data from Global Wind Atlas through an interpolation of data and then bias-corrected with a correction factor.

A similar bias correction approach is applied to the required datasets in this research project. The datasets applied with a bias correction are wind speed, ambient temperature, and solar irradiance. First, the value from secondary datasets Global Wind Atlas (GWA) and Global Solar Atlas (GSA) are applied to the water bodies through the Zonal Statistics tool in QGIS. The tool retrieves the mean value of each weather data for every water body. The 20 years of hourly data from ERA5 is retrieved to measure the mean value of each weather data, and a new raster file is created with a spatial resolution of 250m x 250m. The Zonal Statistics tool applies the new raster file to every water body. A bias correction factor is measured using a comparison between the mean value derived from the new raster file and GWA and GSA, depending on the type of weather data. For example, if the mean wind speed derived from GWA at a particular water body is 10% higher than the mean value wind speed from ERA5 data, then the bias correction factor is 1.1. The bias correction factor was then used to increase each hourly wind speed data in ERA5 data by 10% for that specific water body.

4 Site Selection for FSPV in Indonesia

In this chapter, the selected water bodies location and its total area for FSPV development in Indonesia is presented. First, site selection criterion will be reviewed in order to create an own selection criteria in Section 4.1. Based on the selected criterion, Section 4.2 will present selected water bodies in Indonesia as well as the total available area.

4.1 Site Selection Criteria

4.1.1 Water Conditions and Theoretical Potential

The evaluation process for each group criteria in Table 3-1 is essential in creating the site selection criteria for the research project. The evaluation aims to identify the most important criteria for the FSPV site. First, the theoretical potential of FSPV in Indonesia is calculated based on water bodies availability in Indonesia to further limit the selection of water conditions on whether freshwater FSPV is sufficient enough to support the country's target of 350 GWp installed capacity of Solar PV in 2060 in its Announce Pledges Scenario (IEA, 2022). Figure 4-1 shows the location of freshwater bodies in Indonesia.

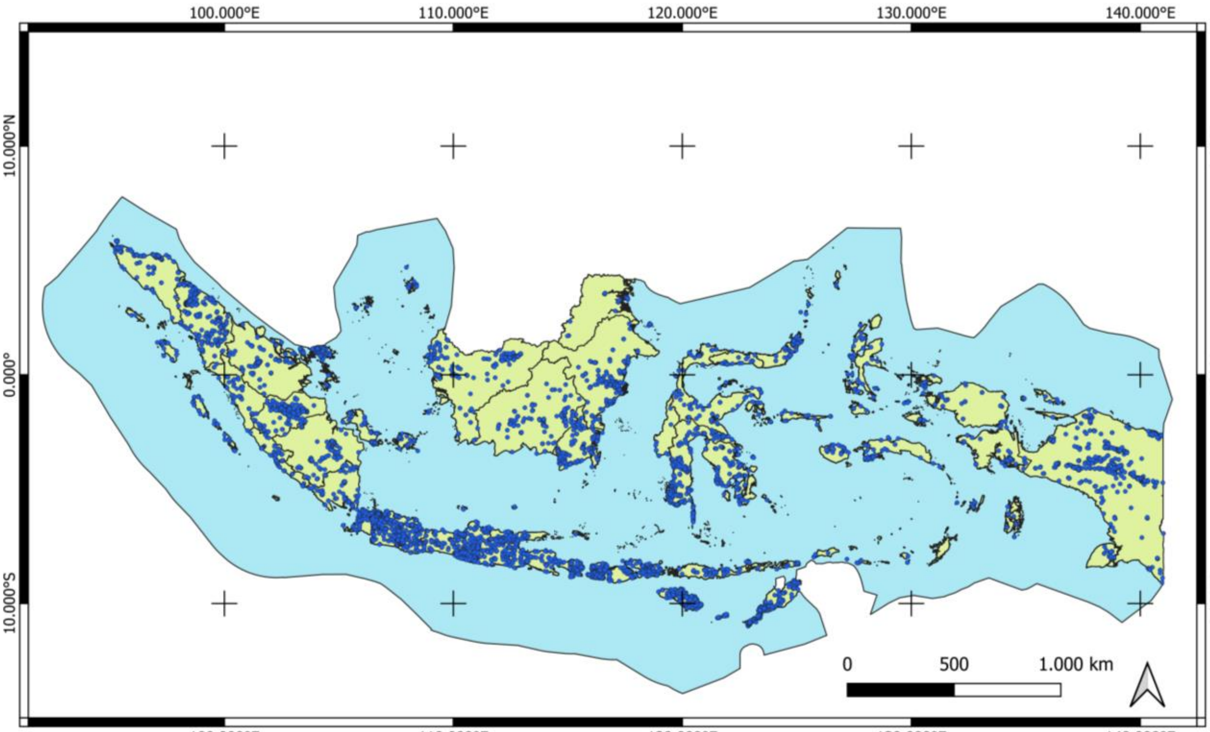

Figure 4-1 Water Body Location in Indonesia

A total of 16,565 freshwater bodies are identified in Indonesia, with a total area of 6,299 km². Theoretically, if all solar PV module is laid in water bodies, with only freshwater FSPV with water occupancy of 27.5%, it is already capable of meeting the target of 350 GWp. However, with the current regulations limiting the water occupancy by 5%, the theoretical potential of freshwater FSPV in Indonesia is 65 GWp, including protected lakes, and 50 GWp, excluding the protected lakes. As a comparison, Silalahi et al. (2021) estimated the potential capacity of freshwater FSPV in Indonesia to be up to 50 GWp.

Meanwhile, as Indonesia is one of the largest archipelago countries, the total area of territorial waters, including the economic exclusive zone in Indonesia, is more than 6 million km². With a similar approach to the theoretical calculation of FSPV in freshwater, the theoretical installed capacity of marine FSPV in Indonesia is up to 1,188 TWp with annual electricity generation up to 1,800 x 10^3 TWh. This figure alone is more than enough to cover the global electricity demand of 25,300 TWh in 2021 (Statista, 2023). However, considering several criteria, such as water depth, wave height, and shipping routes, the technical potential may be far below the figure.

Overall, since the theoretical freshwater FSPV can support Indonesia's ambition in its solar PV target in 2060, the water conditions selected for the research project are freshwater. After selecting freshwater as the water conditions of FSPV in the research, analysis of the other criteria listed in Table 3-1 is required prior to the creation of water bodies selection criteria.

4.1.2 Water Occupancy

Water occupancy is one of the most common criteria for calculating the installed capacity and electricity generation of FSPV. At the moment of this writing, there is no specific guidance or specification available in academic literature or industry environment on what is the maximum occupancy FSPV in a water body. This is mainly because the FSPV itself is still in a nascent stage. Thus, the research on water occupancy still needs to be improved. However, there is a general view that the water occupancy of FSPV will impact the water conditions depending on the occupancy percentage. The potential impacts of having an FSPV system in water bodies are listed below based on several works of literature (Pouran et al., 2022a; Haas et al., 2020):

- Reduction in sunlight reaching the water surface, which may have an impact on photosynthesis and subsequently on the overall food chain
- Impact of leaching and corrosion from materials leads to chemical pollution during the long operational period may become a potential concern
- Impact due to electromagnetic fields, which might have an impact on the aquatic life
- A decrease in oxygen which could release inhibit pollutants from the reservoir bed

Haas et al. (2020) further investigate the impact of different water occupancy of FSPV in the hydropower reservoir in Chile on the growth of algae and hydropower revenue through a simulation model. The research shows that FSPV with a cover of 40% occupancy can be optimal based on the effect of FSPV deployment on algae growth and hydropower revenue. It is identified by Haas et al. (2020) that up until 40% coverage, the impact on hydropower revenue and algae growth is low. There is a slight decrease in algae growth due to the lower oxygen available and sunlight available for photosynthesis in the occupancy percentage of 40%. Meanwhile, the high deployment of FSPV has a detrimental effect on the hydropower revenue due to the reservoir needing to be kept at a certain water level not to have any part of the FSPV system being stranded. The increased water occupancy percentage leads to an increase in the minimum water level in the reservoir, thus limiting the operational flexibility of hydropower and, subsequently, the capability of hydropower to generate electricity. In the water occupancy of 40%, the impact of hydropower revenue is limited. However, the optimal use of 40% water occupancy may vary according to the water body location.

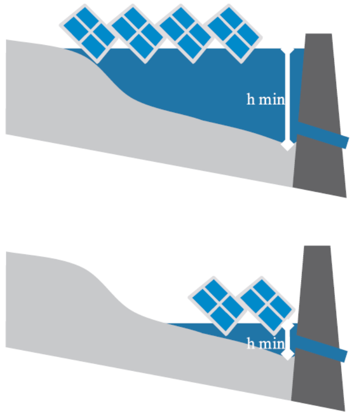

Figure 4-2 Schematic of FSPV Occupancy and Hydropower Reservoir (Haas et al., 2020)

Another study by Château et al. (2019) followed a similar objective to identify the optimal water occupancy of FSPV in a fishing pond in Taiwan. Instead of only using a simulation to find the optimal percentage of water occupancy, the study used an actual measurement on its pilot project. The study shows that a similar percentage of about 40 to 60% occupancy is still acceptable, considering the limited decrease in fish production.

The review of water occupancy criteria is expanded to include a regulation review. Indonesia regulation requires that only 5% of the water bodies be allowed for FSPV installation. To compare, Spain implements three different maximum occupancies, which are 5%, 15%, and 20%, and depends on the water quality and biological activity (Navingo, 2022).

Overall, water occupancy is an essential criterion for FSPV, although not for filtering water bodies but more on the constraint for technical potential. Therefore, a different water occupancy percentage will be used for the research project to cover the current regulation in Indonesia, the uncertainty on the impact of FSPV on water quality, as well as for the reference for stakeholders in Indonesia for a possibility of the increase of percentage occupancy in water bodies.

4.1.3 Water Purpose

Various water body purposes, such as recreational lakes, fishing ponds, hydropower reservoirs, and natural lakes, are identified in the literature for FSPV deployment. However, the only exclusion criteria considered important are the protected and conservation area to prevent the loss of natural ecosystems and species.

On the other hand, Indonesia has a list of national priority lakes that require protection. However, the regulation states that having an energy infrastructure is still possible in the lakes, provided specific environmental assessment requirements must be met. For example, one of the lakes, Singkarak Lake, is listed in the National Electricity Plan for having an FSPV system. The lake already has an installed capacity of a hydropower plant of 175 MW. Therefore, for the rest of the research project, the results will have a differentiation between the inclusion of protected lakes and without the protected lakes.

4.1.4 Maximum Wind Speed

Maximum wind speed is one of the technical limitations for FSPV and the wider context of solar PV. Information on maximum wind load is required in the PV module datasheet for design purposes. The maximum load information is required because modules will move under the action of wind power and create dynamic loads on the system. Excessive wind speed even may cause significant damage to FSPV. There are several incidents identified due to the high wind speed. An incident in Japan in 2019 happened due to the exposure to a wind speed of 33 m/s for several hours, which tore several PV modules, and contact between loose modules and intact modules led to overheating and fire (Bellini, 2019). Another recent incident in 2022 in France happened due to the exposure to a wind speed of 22 m/s leading to the friction of the system and cables connecting the modules to the junction boxes becoming bare, then causing a short circuit and fire (Beyer, 2022).

Figure 4-3 FSPV Incident in Japan (Bellini, 2019)

Therefore, historical maximum wind speed is an important criterion for filtering the water bodies in Indonesia. Furthermore, there is a limitation in designing the maximum wind speed in the current technology of the floating system, which is 30 m/s (Sungrow, n.d.). In addition, a load factor is required to calculate the allowable maximum wind speed. Since no guideline is available for FSPV, a safety factor for land-based solar PV is used. A load factor of 1.7 is used from Banks (2014), with the calculation based on the American Society of Civil Engineers (ASCE) guideline. A historical maximum wind speed of 17.6 m/s is required by dividing the design wind speed by the load factor. This value is close to the value used by Silalahi et al. (2021) of 15 m/s. However, as the load factor is based on land-based solar PV, there is still another missing dynamic load from the water movement that needs to be considered in the load factor. Therefore, the value of 15 m/s is retained for this research project.

4.1.5 Minimum Surface Water Area

The reviewed literature with surface water area as its water bodies selection criteria assumes that with a certain threshold of surface area, the FSPV will not be economically feasible. This might be true considering that with a higher surface area, a higher installed capacity and energy generation may lead to economic of-scale benefits. However, this criterion is not required for determining the technical potential, and the economic attractiveness can also be increased through another path which will be further discussed in Chapters 6 and 7. Therefore, the minimum surface water area is not considered for the research.

4.1.6 Significant Wave Height

The wave height can create a dynamic load into the FSPV system and create a tilting in the PV panels due to the fluctuations in water level (Guo et al., 2021). This parameter is considered more important for deploying marine FSPV. However, there is still a limitation on the significant wave height. For example, the current floating system market can only be around 1.5 – 2 m (Claus & Lopez, 2022). On the other hand, a vessel required for offshore wind projects, such as a Crew Transfer Vessel (CTV) and Service Operation Vessel (SOV), may be required for the installation and during the operating period of the FSPV system. The vessels are considered safe for reaching the project location when a significant wave height is less than 2.3 m (Barthelemy, 2022). However, as the water conditions of water bodies on the land do not experience a similar wave impact as in the ocean, the significant wave height is not considered for the selection criteria in this research.

4.1.7 Water Depth

The greater depths of water bodies may require complex mooring and anchoring solutions. Moreover, diving may be required to check the mooring condition during maintenance. However, it does not mean that it is not possible to have a deep installation. For example, another technology, such as floating offshore wind, is developed for deep water. In addition, for very deep water, the anchoring and mooring of the FSPV system typically use a shore anchoring type (World Bank Group et al., 2019). Therefore, the water depth is not considered for the selection criteria in this research.

4.1.8 Access to Grid and Road

Proximity to road and grid is beneficial for the FSPV project development in terms of cost. However, it does not determine the energy production and design limitation for FSPV. Therefore, proximity to the existing road and grid or substation is not considered as the site selection criteria, although it may have an impact on the economic potential of FSPV deployment in Indonesia.

4.1.9 Solar Resources

Solar irradiance is used as an input for the calculation of energy production from solar PV. However, it does not determine whether solar PV can be installed or not. As an example, one of the installed FSPVs is installed in France, where the GHI value is only around 1,500 kWh/m^2. Using the criteria determined in the reviewed literature in Table 3-1, the FSPV should not be installed as it is considered unsuitable. However, the FSPV is still installed and in operation. Therefore, solar resources are not considered as the site selection criteria for FSPV in this research.

4.1.10 Summary for Site Selection

In summary, the selection criteria in the literature in Table 3-1 used various constraints to develop FSPV. A total of 10 criteria are reviewed and can be grouped as technical, economic, and environmental criteria. Six technical criteria are identified: water condition, maximum wind speed, significant wave height, water depth, and solar resources. Three economic-related criteria are identified: minimum surface water area, access to grid/substation, and proximity to the road. Meanwhile, two environmental criteria are identified: water occupancy and water purpose. Some criteria, such as wind speed, limit the selection of water bodies for FSPV. However, other criteria may be considered suitable for considering FSPV cost components, such as access to the grid and road. Based on the review of each criterion, a water bodies selection criteria for the research project is developed and shown in Table 4-1.

Table 4-1 Water Bodies Selection Criteria

Criteria	Remarks
Water Conditions	Freshwater
Water Occupancy	Use different percentage: 5%, 10%, 20%, 40%
Maximum Wind Speed	15 m/s
Protected Areas	National Priority Lakes will be studied as an if condition due to the possibility of having energy infrastructure

4.2 Selected Water Bodies

Indonesia has many freshwater locations throughout the country, as shown in Figure 4-1. As the water bodies selection criteria have already been developed, thus the water bodies for FSPV deployment in Indonesia can be selected. First, the water bodies will be categorized based on historical maximum wind speed in the past 20 years, protected lakes or not, as well as differentiation based on water occupancy. Using the bias-corrected data of ERA5 wind speed data and information on the list of protected lakes, water bodies are categorized and shown in Figure 4-4.

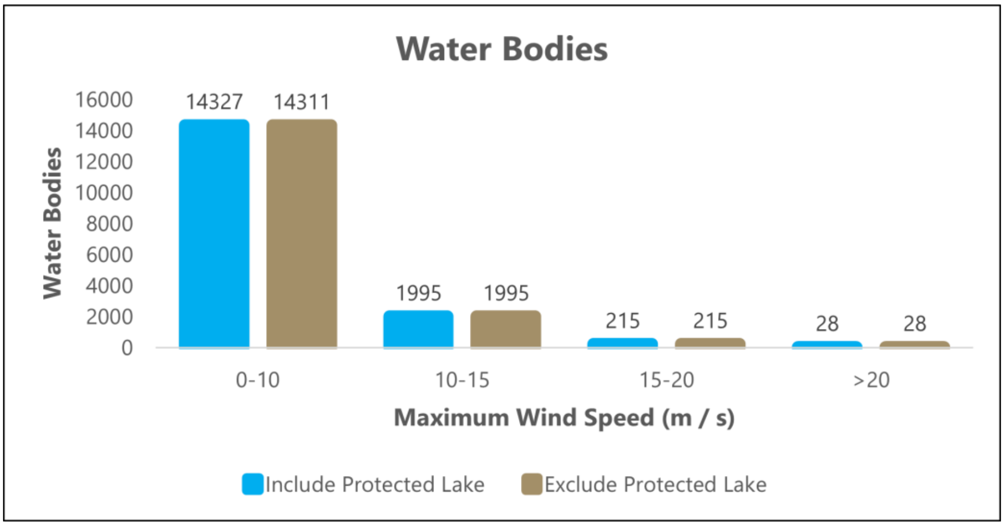

Figure 4-4 Water Bodies Categorization Based on Wind Speed

Figure 4-4 shows the total water bodies based on the historical wind speed and whether the protected lakes are included. The result shows that most water bodies are located in the low wind speed region. This figure is aligned with the research by Langer et al. (2022), which shows that Indonesia is a country with a low resource of wind. Only 243 water bodies are more than the maximum wind speed criteria for site selection. On the other hand, all of the protected lakes in Indonesia have a historical maximum wind speed of less than 10 m/s. The information on the total area of each water bodies then retrieved from the QGIS to show the difference between the categories. Figure 4-5 shows the result of the water body's area.

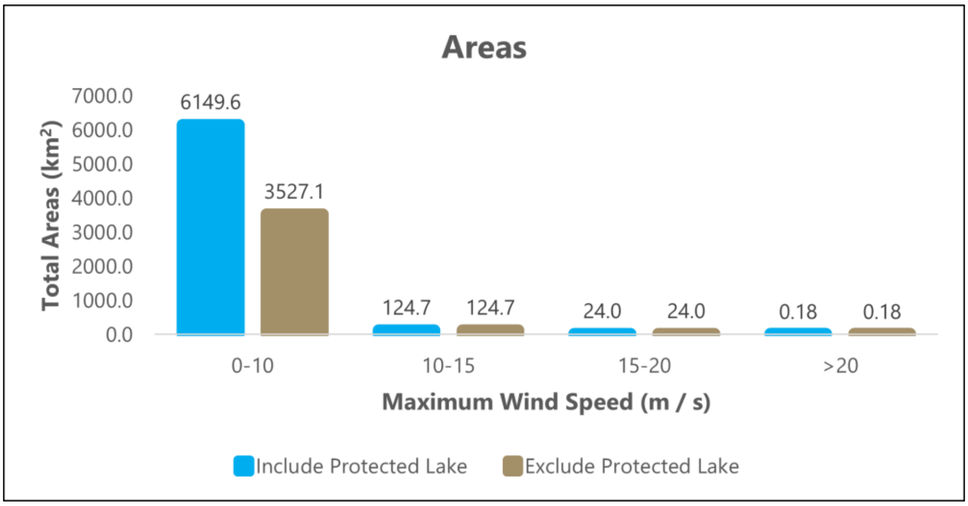

Figure 4-5 Water Bodies Area Based on Wind Speed

Since there are only 243 water bodies in the region with a historical maximum wind speed of more than 15 m/s out of 16,565 water bodies in Indonesia, it is not surprising that the total area is only 24.18 km^2. However, there is a finding that the protected lakes have a considerable water body area with a total area of 2,623 km^2, even though the protected lakes only accounted for 16 water bodies in Indonesia. Furthermore, the water bodies area from the protected lakes alone already covered 42% of the total water bodies area in Indonesia. The inclusion of protected lakes in determining the potential deployment of FSPV in Indonesia may become an important parameter. Based on the information of the total available area for each water body, a suitable area with different water occupancy percentages and the exclusion area is shown in Table 4-2.

Table 4-2 Water Bodies Summary

Water Occupancy	Suitable Area [km^2]	Protected Lakes Area [km^2]	Excluded Wind Speed Area [km^2]
5%	176.4	131.1	1.2
10%	352.7	262.3	2.4
20%	705.4	524.5	4.8
40%	1,410.8	1,049.0	9.7

Figure 4-6 shows the distribution of selected water bodies as well as the location of the protected lakes and the excluded water bodies. The location of suitable water bodies and their total area, including the protected lakes, will be used for the calculation of the technical potential of FSPV, which will be addressed in the next chapter.

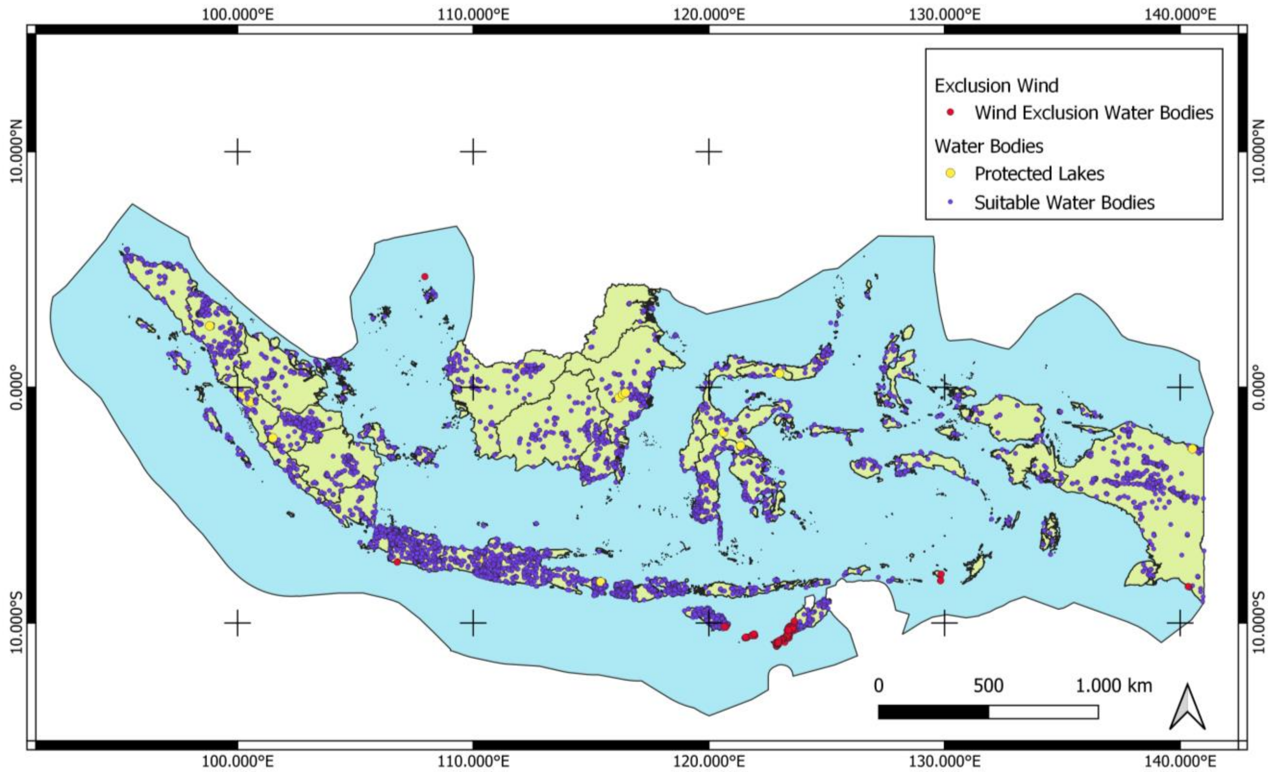

Figure 4-6 Location of Selected Water Bodies

5 Technical Potential of FSPV in Indonesia

In this chapter, the technical potential of FSPV in Indonesia is calculated. First, the installed capacity potential will be shown in Section 5.1. The installed capacity potential is calculated for each selected water body from Chapter 4 and based on the technical limitations such as the effective area and water occupancy. The annual electricity generation potential will be presented in Section 5.2 through three different methods. The method will then be compared, and an analysis of the capacity factor will be presented. Section 5.3 will analyze the possibility of covering the electricity demand in the country based on the identified technical potential.

5.1 Installed Capacity Potential

Every water bodies in Indonesia have a different total water body area, and there are different water occupancy analyzed in the research as listed in Table 4-1, which are 5%, 10%, 20%, and 40%. Based on the calculated area from QGIS, the installed capacity potential in each water body is calculated using equations 1-3 in Chapter 3. The calculation already considered the effective area and limitation on the water occupancy. Figure 5-1 shows the distribution of installed capacity potential in Indonesia by using map generation in QGIS at 5% water occupancy.

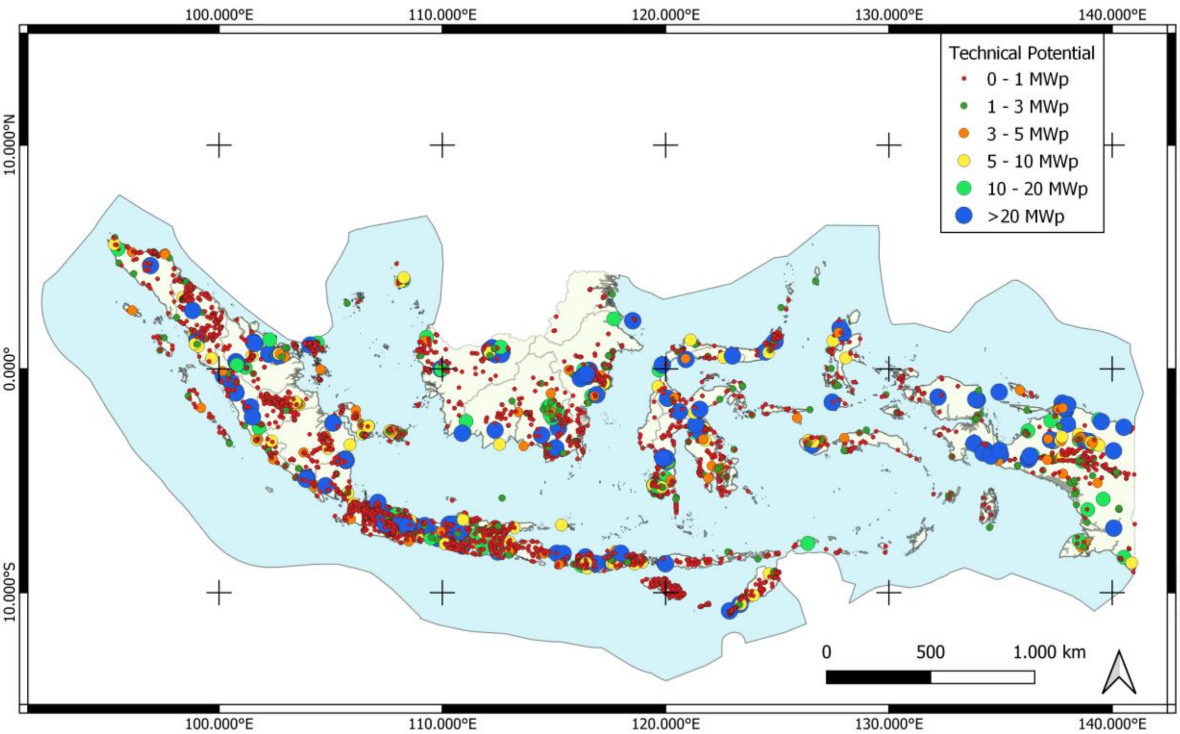

Figure 5-1 Installed Capacity Potential (in MWp) Map of FSPV in Indonesia – 5% Water Occupancy

Figure 5-1 presents the location of water bodies suitable for FSPV installation based on the size categorization. The map shows that the water bodies are mostly located on Java Island, albeit with relatively low potential capacity in each water body. In addition, the map only shows the location of suitable water bodies and protected lakes installed capacity potential, thus excluding the location where the wind speed is above the selection criteria. Based on the 5% water occupancy, the country boasts an installed capacity potential of FSPV at 19,444 MWp without protected lakes and can be up to 33,409 MWp if the protected lakes are included. Moreover, the installed capacity potential can be even higher, up to 267,300 MWp at 40% water occupancy. Figure 5-2 shows the installed capacity potential at different water occupancies level.

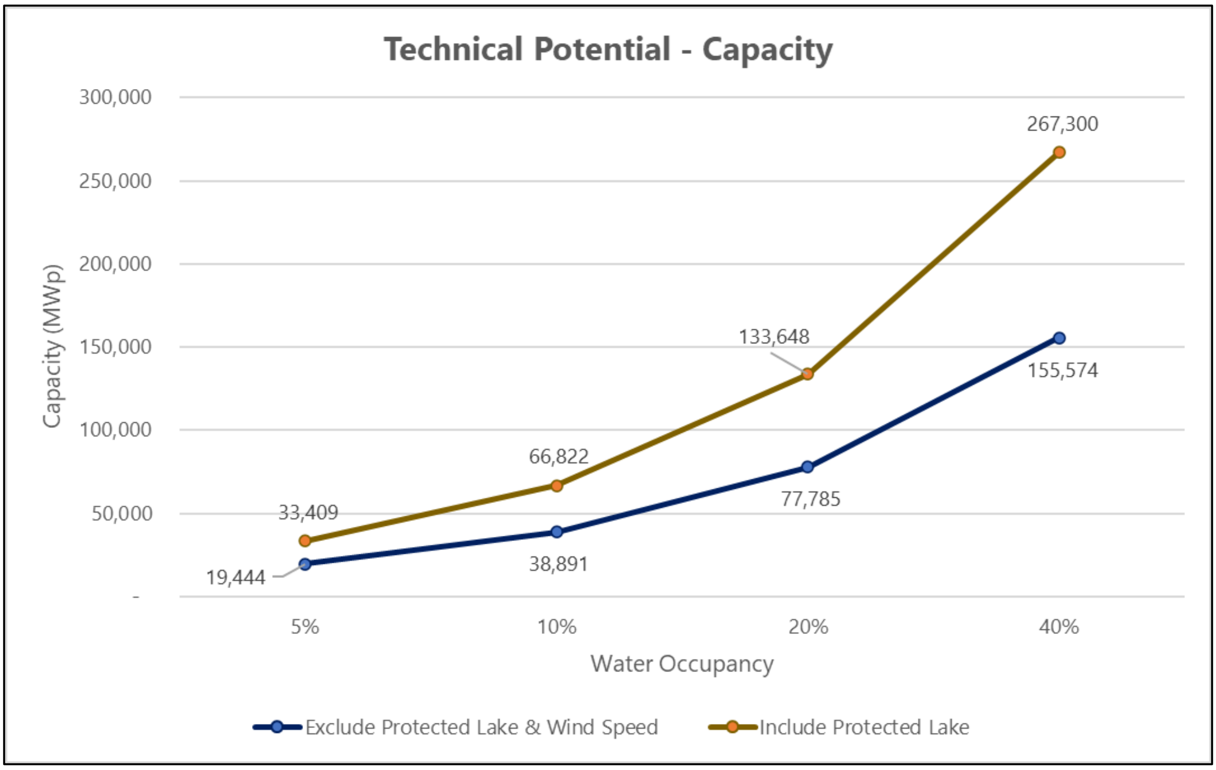

Figure 5-2 Installed Capacity Potential of FSPV in Indonesia

Based on Figure 5-2, the technical potential of FSPV is decreased compared to the theoretical potential calculated in Chapter 4. For example, the theoretical potential is estimated at 50 GWp at 5% water occupancy without considering the protected lakes, while the technical potential arrived at 19.4 GWp. This is because the installed capacity potential is already considered constrained by the effective area and area occupancy, limiting the possibility of laying the PV module in the water body. However, even though technical limitations have already been implemented, the FSPV technical potential is still able to support a considerable share of the country's target of 350 GWp of solar PV by 2060.

As mentioned in previous paragraphs, most water bodies are on Java Island. A total of 6,581 suitable water bodies out of 16,322 selected water bodies, or around 40% of water bodies, are identified in Java Island. Meanwhile, the installed capacity potential in Java Island is estimated at 2,813 MWp at 5% water occupancy and up to 23,184 MWp at 40% water occupancy. These installed capacities only represented 8.5% of the country's total installed capacity potential at both water occupancy levels. This may happen because Java Island is the most populated island in Indonesia. Hence the potential of manmade water bodies on a smaller scale is higher in the region, which increases the total number of water bodies.

Meanwhile, the country's most potential provinces to deploy FSPVs are Sumatera Utara, Sulawesi Selatan, and Papua. Table 5-1 shows the installed capacity of these provinces.

Table 5-1 Most Installed Technical Potential (in MWp) Provinces

Province	Water Bodies	5%	10%	20%	40%
Sumatera Utara	1,336	6,162	12,324	24,649	49,298
Sulawesi Selatan	897	5,221	10,443	20,886	41,773
Papua	880	3,662	7,323	14,647	29,294

The provinces in Table 5-1 are having the most potential installed capacity of FSPV due to the presence of large lakes in the region including the protected lakes. Even though the protected lakes are excluded, these provinces are still the region where installed capacity potential is considered high compared to the other provinces. Details of every province's installed capacity potential are presented in Appendix A.

5.2 Annual Electricity Generation Potential

The annual electricity generation potential is calculated using three different methods: Simple, FSPV Modified, and Time Series. As for Time-Series, only seven water bodies are investigated as a sample locations. Meanwhile, the Simple and FSPV Modified method will calculate the electricity generated in all selected water bodies. In addition, an analysis of the effect of FSPV deployment on a capacity factor will be performed based on the results of the three methods. The result of the capacity factor analysis will add to the currently available research on FSPV. Meanwhile, the annual electricity generation potential will be used to determine the economic potential of FSPV in Indonesia.

Details of the electricity generation potential of every province are shown in Appendix A.

5.2.1 Simple Method

The simple method does not consider any effect of environmental conditions such as ambient temperature and wind speed for the calculation of electricity generation. Instead, it is using the module efficiency information from the datasheet which is based on standard test conditions. Figure 5-3 shows the national electricity generation potential from FSPV in Indonesia based on the difference in water occupancy and the inclusion of protected lakes.

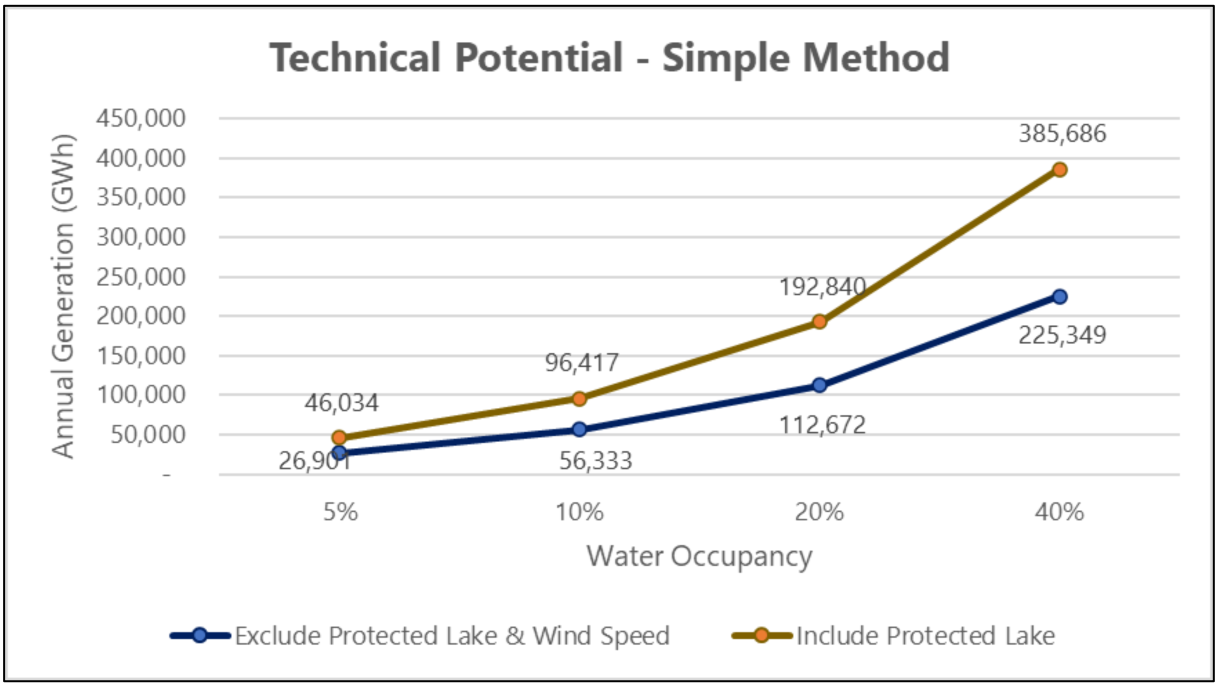

Figure 5-3 Annual Electricity Generation Potential of FSPV in Indonesia – Simple Method

As in the case of installed capacity potential, the national annual electricity generation trend in Simple Method follows the same trend of increment. Sumatera Utara, Sulawesi Selatan, and Papua are still the provinces with the largest annual electricity generation in Simple Method.

However, if an analysis is performed in provincial details, the correlation between installed capacity and electricity generation may be complex. With a similar range of installed capacity of FSPV, a different annual electricity generation may be identified. This is because the most important parameter in Simple Method is the solar irradiance, as the other parameter is kept at standard test conditions. The solar irradiance will vary in different water bodies, thus changing the result of electricity generation even though it has a similar size of installed capacity. For example, Kepulauan Riau has a potential installed capacity of 273 MWp and annual electricity generation of 350 GWh at 5% water occupancy. Meanwhile, Nusa Tenggara Timur has less potential installed capacity of 215 MWp, but it can generate annual electricity generation of 360 GWh, which is higher than Kepulauan Riau. This is because the annual solar irradiance in Nusa Tenggara Timur is higher than in Kepulauan Riau.

The Simple Method is able to provide the estimation of the electricity generation potential of FSPV in Indonesia. However, there still needs to be environmental considerations that affect the module efficiency and, subsequently, the electricity generation. Therefore, the FSPV Modified method will be used to close this gap.

5.2.2 FSPV Modified Method

FSPV Modified method is a specific mathematical model for floating solar PV that already considers environmental data for its calculation, such as wind speed and ambient temperature. The wind speed and ambient temperature will affect the module efficiency and, subsequently, the electricity generated from the FSPV plant. Therefore, the annual electricity generation from the FSPV Modified method is expected to be different from the Simple method, either higher or lower depending on the weather conditions. The result of the FSPV Modified method is shown in Figure 5-4.

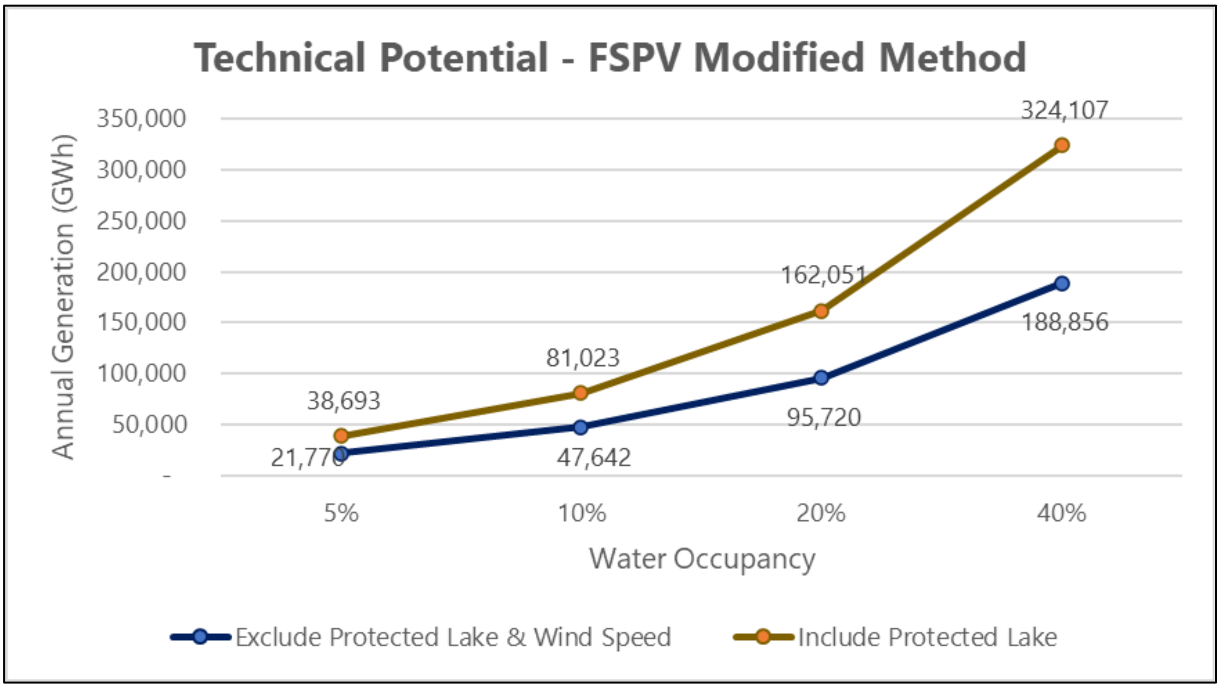

Figure 5-4 Annual Electricity Generation Potential of FSPV in Indonesia – FSPV Modified Method

Based on Figure 5-4 and compared with Figure 5-3, the annual electricity generation from the FSPV Modified method is less than Simple Method. Sumatera Utara, Sulawesi Selatan, and Papua are still the largest sources of potential generation from FSPV. In addition, the electricity generation potential from every province in the FSPV Modified method is also lower than the Simple method.

There is no province in the FSPV method with a higher annual electricity generation than the Simple method. This phenomenon can be explained by the weather conditions in Indonesia, which are the additional parameters in the FSPV Modified method. The mean ambient temperature in Indonesia based on bias-corrected 20 years of ERA5 data is 26.6°C. This value is higher than the standard test conditions, which are 25°C. As extracted from the module datasheet, there is a decrease of 0.35% in power output with every increase of 1°C. In addition, Indonesia is a low resource of wind speed with a mean wind speed in Indonesia based on bias-corrected 20 years of ERA5 data is 4 m/s. The effect of low wind speed will lead to less available convection cooling to the PV module, thus increasing the module temperature and subsequently lowering its efficiency.

The spatial results of electricity generation (in GWh) for each province from the FSPV Modified method are shown in Figure 5-5. This figure is shown due to the economic potential calculation requiring a certain location factor for every province in Indonesia and also to show the distribution result of annual electricity generation of FSPV by provinces in Indonesia.

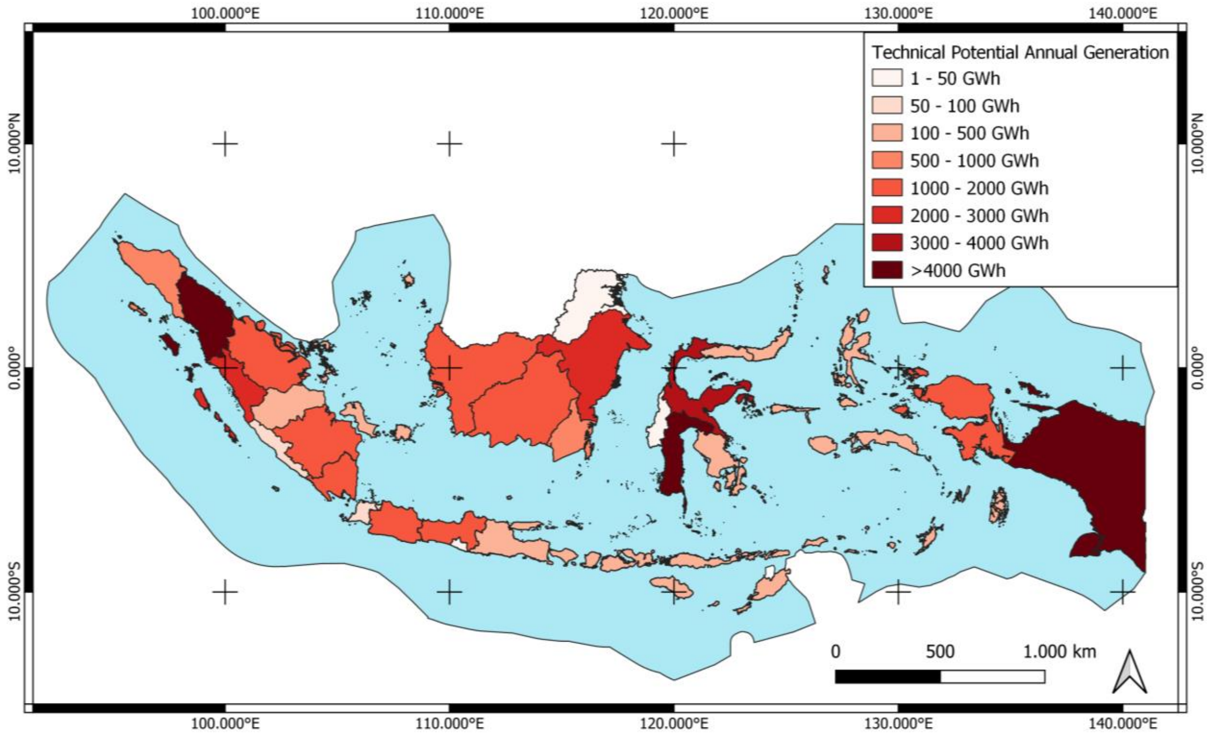

Figure 5-5 Technical Potential Annual Generation – 5% Water Occupancy

5.2.3 Time-Series Method

The Time Series Method used hourly datasets for its calculation, thus providing a more detailed approach than the other method. First, the module tilt for 7 sample locations is determined based on the possible optimum solar irradiance that the location may receive. Since Indonesia is located on the equator, low module tilt is expected to be the optimum solution for solar PV installation in Indonesia. Separately, there is a limitation as well from the floating system as the maximum module tilt for the system is 20° from the selected supplier to avoid a problem that may arise due to dynamic load in water bodies from wind and water. Selected module azimuth (to determine whether the module is facing north or south) and module tilt for each location are shown in Table 5-2.

Table 5-2 Module Azimuth and Module Tilt (in degree) for Sample Locations

Location	Azimuth	Tilt
Singkarak Lake	0	5
Wonorejo Reservoir	0	9
Sentani Lake	0	5
Manggar Reservoir	0	5
Towuti Lake	0	5
Patamawai Lake	0	12
Cirata Reservoir	0	10

Based on the selected module tilt and azimuth, the hourly total solar irradiance to the module can be calculated using Equations 5-8. The result of the hourly irradiance, together with ambient temperature and wind speed, will be used to calculate the hourly operating module efficiency using Equations 9-14. Finally, as the hourly module efficiency is known, the hourly generation from the FSPV can be calculated by using Equation 15. The result of annual electricity production from each sample water body are shown in Table 5-3.

Table 5-3 Annual Electricity Generation in Sample Water Bodies – Time Series Method

Location	Electricity Production [GWh]	Energy Density [kWh/m^2]	Capacity Factor [%]
Singkarak Lake	743 – 778	261 – 275	14.7 – 15.4
Wonorejo Reservoir	25 – 26	264 – 279	15.0 – 15.7
Sentani Lake	656 – 686	270 – 283	15.1 – 15.9
Manggar Reservoir	26 – 27	239 – 248	13.4 – 14.1
Towuti Lake	4,170 – 4,370	278 – 291	15.6 – 16.3
Patamawai Lake	0.58 – 0.60	301 – 316	16.9 – 17.7
Cirata Reservoir	446 – 467	283 – 296	15.9 – 16.6

Table 5-3 shows the annual electricity production for every sample water body, with the highest being Towuti Lake. Towuti Lake can generate a higher electricity production because it has the highest availability area and installed capacity compared to the other samples. Therefore, to understand which location is able to generate electricity efficiently, energy density and capacity factor are presented. The energy density shows the annual electricity generated in every meter square in that water body. Meanwhile, the capacity factor shows the ratio of the actual power generated by FSPV over time divided by nominal power to measure how often the FSPV is able to operate annually. Using these figures, Patamawai Lake in Nusa Tenggara Timur becomes the location with the highest energy density and capacity factor.

The result from Time Series Method then will be compared with the other method to investigate the efficiency of floating solar as well as compare the method itself in Section 5.2.4.

5.2.4 Method Comparison

Since the Time Series method formula is based on land-based solar PV, thus elements that may have a role in floating solar PV may not be captured precisely such as the cooling effect of water on the module efficiency. First, a comparison of the average capacity factor between the Simple method and FSPV modified method is presented in Figure 5-6.

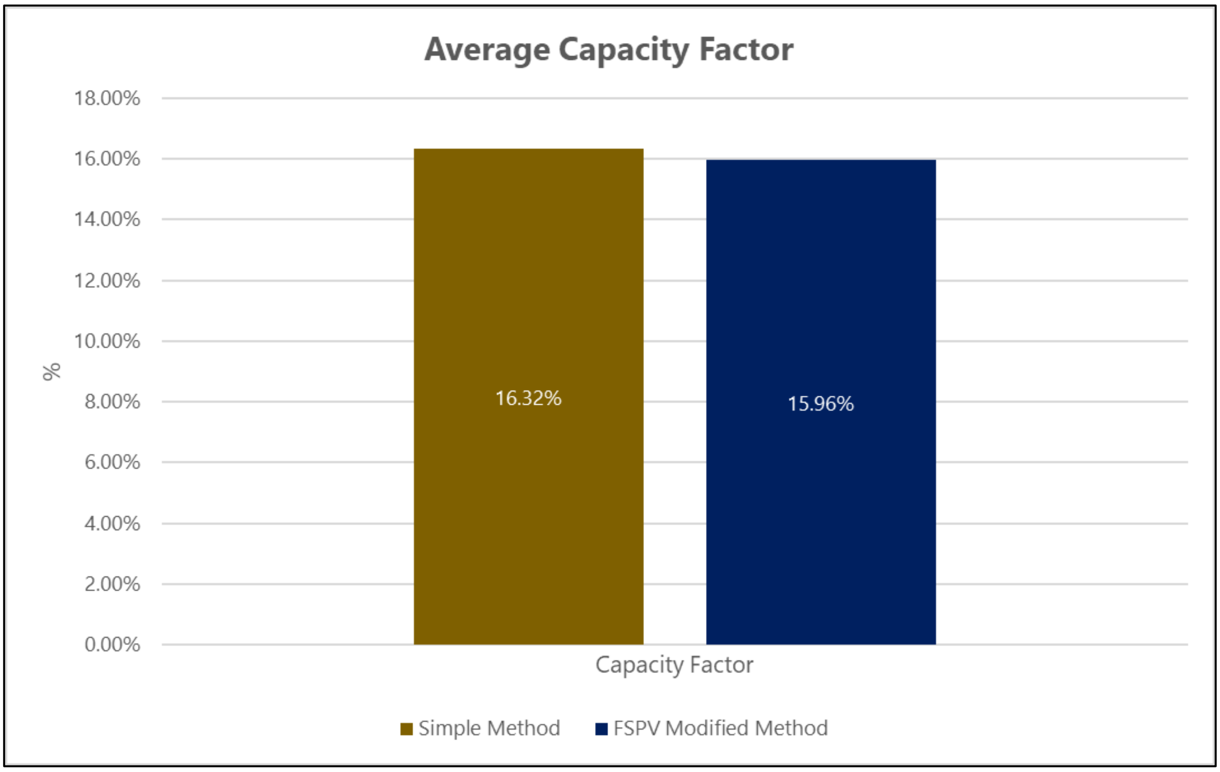

Figure 5-6 Average Capacity Factor of FSPV in Indonesia

As expected and shown in Figure 5-6, the average capacity factor in Indonesia with the FSPV Modified method is lower than Simple Method. This is mainly due to the effect of ambient temperature and wind speed in Indonesia that is lowering the module efficiency in the FSPV Modified method. As a comparison, Silalahi et al. (2021) calculated an average capacity factor of 15.4% for Indonesia using System Advisor Model (SAM). However, it is to be noted that SAM does not have features for floating solar PV. Another study by Pouran et al. (2022b) also uses SAM to calculate electricity generation, but the study used an additional assumption of increasing the module efficiency by 10%. It is assumed that the figures in Silalahi et al. (2021) are applicable to land-based PV as the study does not mention which type of solar PV represents the 15.4% figure. Nevertheless, the average capacity factor of FSPV using the FSPV Modified Method stands higher than the study from Silalahi et al. (2021), presumably due to the cooling effect, while for the Simple method due to the use of standard test conditions in its calculation. The average capacity factor between the three methods in sample water bodies then are compared in order to see the differences, as presented in Table 5-4.

Table 5-4 Method Comparison – Capacity Factor (%)

Location	Simple	FSPV Modified	Time Series
Singkarak Lake	14.9 – 15.6	14.7 – 15.3	14.7 – 15.4
Wonorejo Reservoir	16.0 – 16.8	15.5 – 16.2	15.0 – 15.7
Sentani Lake	15.9 – 16.7	15.3 – 16.1	15.1 – 15.9

Location	Simple	FSPV Modified	Time Series
Manggar Reservoir	14.3 – 15.0	13.9 – 14.5	13.4 – 14.1
Towuti Lake	16.6 – 17.3	16.1 – 16.8	15.6 – 16.3
Patamawai Lake	17.9 – 18.8	17.4 – 18.1	16.9 – 17.7
Cirata Reservoir	16.3 – 17.1	15.8 – 16.5	15.9 – 16.6

There are ranges of a capacity factor in all three methods as the methodology to arrive at the electricity generation used an assumption of Performance Ratio between 78.8% to 82.5%. The Simple method generally produces the highest average capacity factor, while the Time Series method becomes the lowest. As discussed before, the Simple method is able to produce a higher capacity factor due to the formula used in the method considered the standard test conditions. Meanwhile, the Time Series method has the lowest average capacity factor, presumably due to the method itself being more applicable for ground-mounted solar PV; thus, do not consider possible cooling effects in water, although the albedo of water is considered for the Time Series method. Moreover, the average capacity factor in the Time Series method is 15.5%, which is closer to the result from Silalahi et al. (2021).

Although, on average, the FSPV Modified method produces a higher capacity factor than the Time Series method, Singkarak Lake and Cirata Reservoir have a slightly lower capacity factor than the Time Series method. The mechanism of the calculation of the FSPV Modified method can explain this. Since the FSPV Modified method used the daily average value of ambient temperature and wind speed, the datasets during the night will be considered for calculating the average value. As an example, the wind speed during the day in Cirata reservoir is 1.8 m/s. However, the daily average is 1.6 m/s due to the wind speed during the night being only 1.4 m/s. Since the value of daily average wind speed is used for the FSPV method, thus the convectional cooling from the wind is slightly lower, leading to a slightly lower capacity factor compared to the Time Series method, which uses the hourly wind speed during the day only.

A validation check with another study (Sukarso & Kim, 2020) is then performed for Cirata Reservoir. The study investigates the cooling effect of floating solar PV in Cirata by comparing it with ground-mounted solar PV in Cirata dam. Sukarso & Kim (2020) calculates the technical potential of 1,439 GWh for 1 MWp FSPV in Cirata Reservoir and 1,396 GWh for the ground-mounted scenario. These equate to a 16.4% capacity factor FSPV scenario and 15.9% for the ground mounted. Both results fall within the FSPV Modified and Time Series methods; however, the ground-mounted scenario lies within the lower range, while the floating solar case lies within the higher range. From the validation check, the result from this study is in a similar range to the other study by Sukarso & Kim (2020).

Since FSPV Modified Method considered the environmental conditions in its formula calculations and calculated for all suitable water bodies, the electricity generation from FSPV Modified Method will be used for economic potential. The electricity generation will be the component of electricity production in the LCOE calculation.

5.3 Technical Potential and Demand Coverage Assessment

The capability of technical potential of FSPV in Indonesia to supply the electricity demand will be assessed through a comparison with the latest actual data on electricity consumption per province from Central Agency on Statistics (BPS-Statistics Indonesia, 2022). The information will be retrieved and compared with the annual potential generation of FSPV in the respective provinces. In addition, an assessment of future demand coverage will based on the estimated value from IEA (2022) where an average increase of electricity demand of 4% per year is used. The result of the comparison at 5% water occupancy is shown in Figure 5-7 and 5-8.

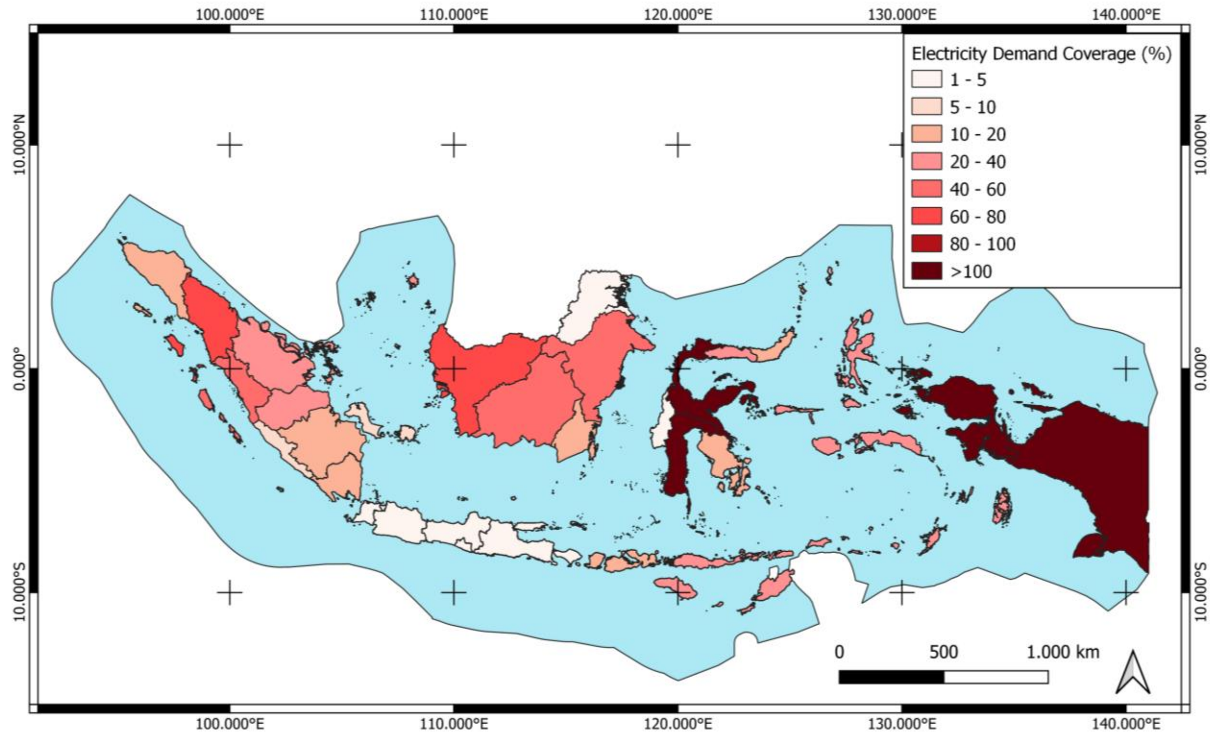

Figure 5-7 Demand Coverage Technical Potential – 5% Water Occupancy (Based on Current Demand)

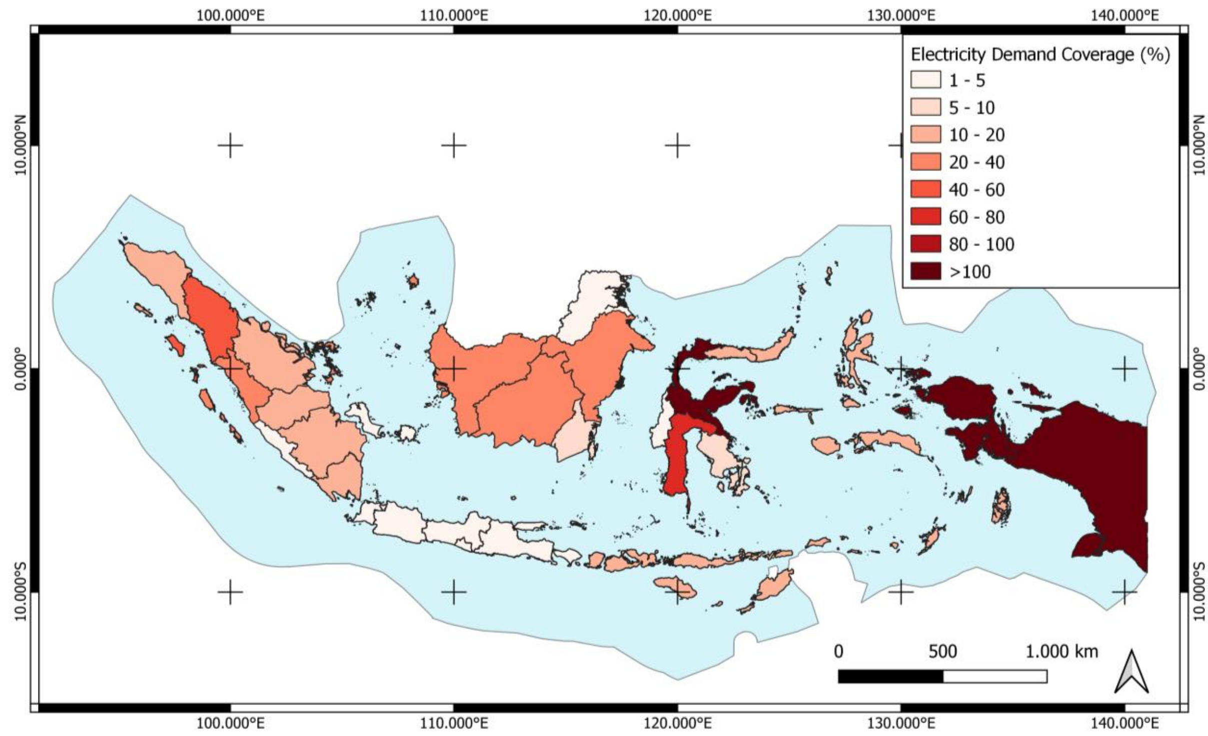

Figure 5-8 Demand Coverage Technical Potential – 5% Water Occupancy (Based on 2030 Projected Demand)

Based on Figure 5-7, the technical potential FSPV is able to supply at least a quarter of the electricity demand in 16 provinces in Indonesia. In addition, there are four provinces that the FSPV can supply more than electricity demand: Papua, Papua Barat, Sulawesi Selatan, and Sulawesi Tengah. Meanwhile, the demand coverage will be less in 2030 considering the projected growth of electricity demand. However, Papua, Papua Barat, and Sulawesi Tengah is still able to supply more than electricity demand in 2030. In addition, the FSPV still can supply at least 10 percent of electricity demand in 19 provinces if there are no changes in the water occupancy regulation. Details of the demand coverage of every province are shown in Appendix C.

It is also noticeable that the FSPV still holds considerable electricity demand coverage in the provinces outside of Java Island. This is due to the demographic situation in Indonesia, where Java Island is the most populated island in the country. Hence the electricity demand is higher on this island. Although not shown in Figure 5-7 and 5-8, the import and export distribution of electricity between provinces in Indonesia is possible between the provinces located on the same island. For example, in Sulawesi, if the excess generation from FSPV in Sulawesi Selatan and Sulawesi Tengah is distributed to its neighboring provinces, the annual electricity generation from FSPV in Sulawesi Island is capable of supplying all electricity demand in the island.

6 Economic Potential of FSPV in Indonesia

In this chapter, the economic potential of FSPV in Indonesia is calculated. The result of economic potential is shown in Section 6.1. The economic potential is calculated based on the LCOE method by using the cost information in Chapter 3 and the annual electricity generation of the FSPV Modified method. Section 6.2 then will analyse the potential of FSPV deployment in a wider context namely electricity demand coverage.

6.1 Economic Potential Result

The economic potential of FSPV in Indonesia is determined using a comparison between the result of the LCOE calculation on each water body and the applicable ceiling prices in Indonesia. The LCOE represents the break-even value of electricity cost and calculated based on the capital cost and operating cost in Table 3-10 in Chapter 3. As one of the parameters for LCOE calculation is annual electricity production, the annual electricity generation from the FSPV Modified method is used. Furthermore, electricity production is assumed to be degraded yearly as in Table 3-10. Since all provinces in Indonesia have different ceiling prices, then the LCOE result needs to be compared with its respective provinces' ceiling prices. Figure 6-1 shows the distribution of economic potential in Indonesia by using map generation in QGIS at 5% water occupancy. Details of the economic potential of every province are shown in Appendix B.

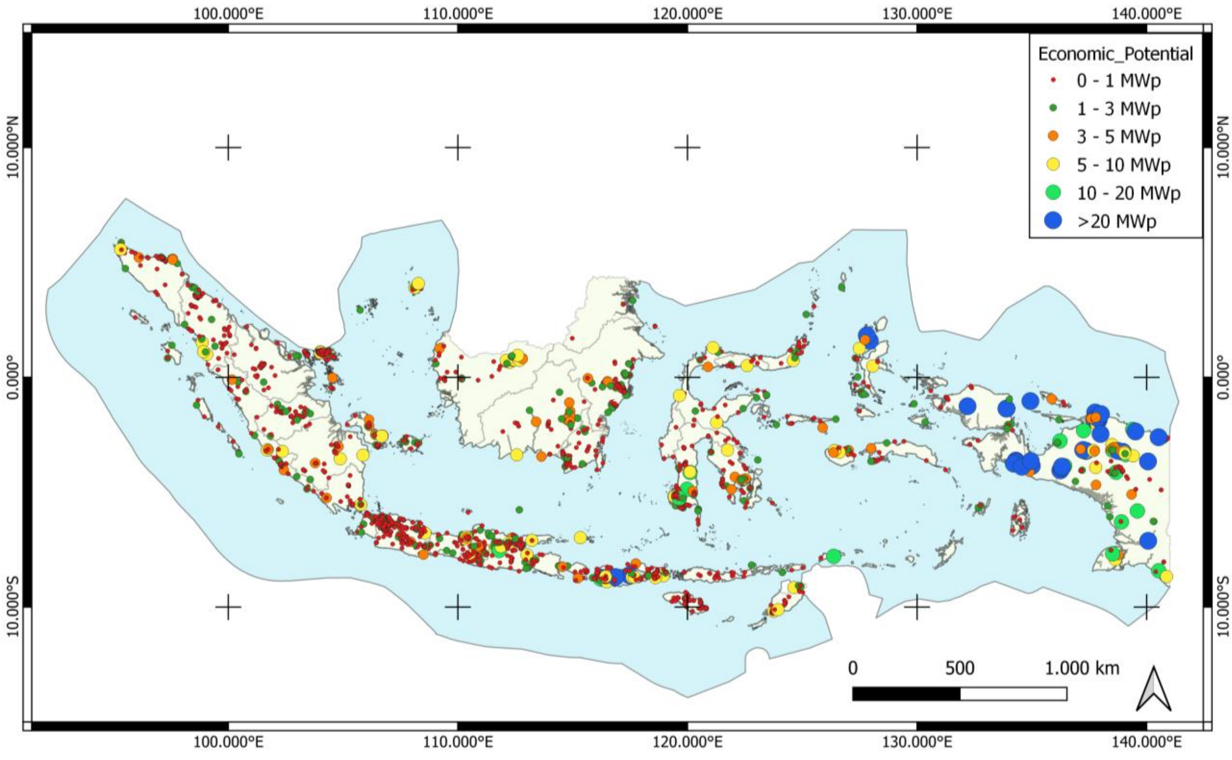

Figure 6-1 Economic Potential (in MWp) Map of FSPV in Indonesia – 5% Water Occupancy

Figure 6-1 shows the location of water bodies where the LCOE result is lower or equal to the ceiling prices based on the size categorization in the ceiling prices regulation. The map shows that an FSPV installation with less than 1 MWp is more attractive than a larger installed capacity. It is also shown that the water bodies are mostly located in Java Island since it has considerable amounts of water bodies with a capacity of less than 1 MWp as discussed in Chapter 5. A larger capacity such as 10 to 20 MWp and more than 20 MWp is considered attractive in addition to the smaller capacity in the eastern region of Indonesia. Figure 6-2 shows the economic potential at different water occupancies level including the comparison with the technical potential.

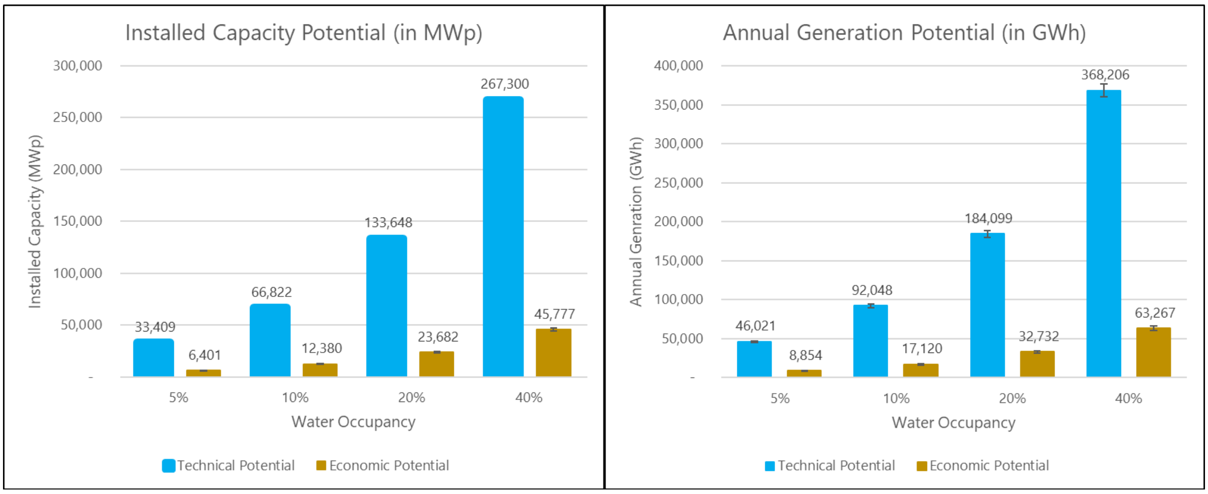

Figure 6-2 Economic Potential vs Technical Potential

As can be seen in Figure 6-2, there is a significant drop in potential from technical to economic potential. This drop is due to the implementation of ceiling price as a parameter for determining economic potential. There is a decline in the ratio of the economic potential to the technical potential of FSPV from 19% at 5% water occupancy to 17% at 40% water occupancy. This is because the increase in the maximum water occupancy will lead to a larger installed capacity where the ceiling price is lower than at small capacity and hence become less economically attractive. In addition, the rest of the technical potential that is not accounted for in the economic potential has LCOE results that are above the ceiling price and thus not included in the economic potential. Figure 6-3 is presented to show the LCOE distribution of FSPV in Indonesia and its ceiling prices.

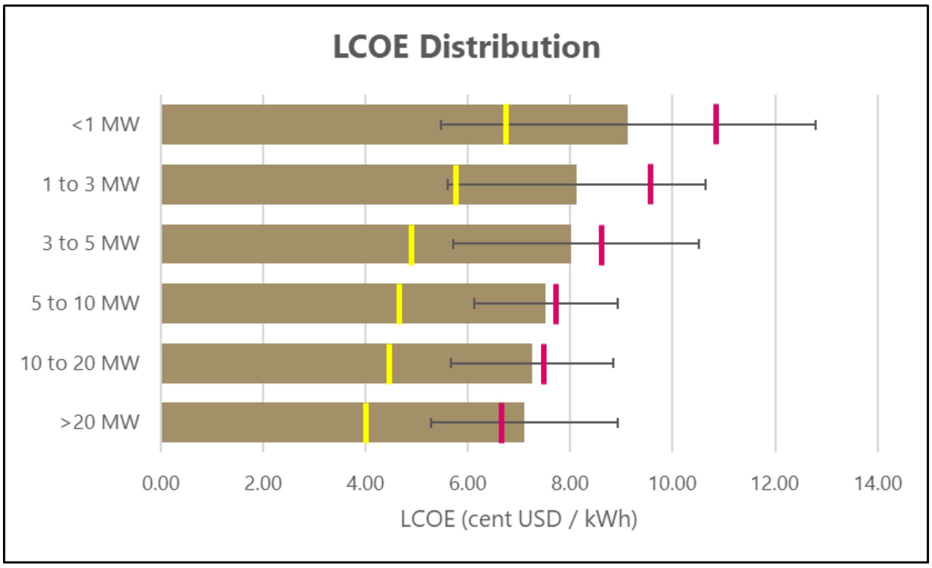

Figure 6-3 LCOE Distribution and Ceiling Prices (Red Line: Ceiling Price from Year 1 to 10; Yellow Line: Ceiling Price from Year 11)

Based on Figure 6-3, there is a decrease in LCOE by increasing the installed capacity. This is due to the differences in the higher electricity production in the large-scale FSPV, which is mainly observed in the eastern part of Indonesia compared to the smaller scale. Higher electricity production will reduce the

LCOE value. The figure also shows two ceiling prices indicated by the red and yellow lines. The yellow line shows the ceiling price from year 11. Meanwhile, the red line shows the ceiling price from years 1 to 10, where the multiplier of the location factor is 1, as in Table 3-7. The location factor will shift the red line to the right. The ranges of LCOE on the right side of the red line may be economic potential and depends on which provinces the water body is located in and the applicable ceiling prices in Table 3-6 in Chapter 3. However, as two ceiling prices are applicable based on the year of operation, determining economic potential also depends on the ceiling price from year 11, as shown in the yellow line. This yellow line has no location factor, as in Table 3-6.

The FSPV will be deemed economically potential if the electricity prices from the FSPV can meet both ceiling prices, years 1 to 10 and from year 11. However, there will be a case where the calculated LCOE is lower than the ceiling price from years 1 to 10 but higher than from year 11. Therefore, the calculated LCOE needs to be adjusted to meet the ceiling price requirement. In simple terms, the electricity prices in the first ten years need to be high enough to cover the cash flow throughout the operational period despite the lower ceiling price from year 11.

For example, there is a water body in Aceh with an installed capacity potential of 2.3 MWp with a calculated LCOE of 6.78 cents USD/kWh. The applicable ceiling prices for this location are 10.38 cents USD/kWh for years 1 to 10 and 6.23 cents USD/kWh from year 11. Since the calculated LCOE is higher than the ceiling price from year 11, the electricity price value needs to be adjusted by increasing the electricity cost per kWh in the first ten-year operation. In order to meet the ceiling prices, the first ten-year electricity cost will be increased to 7.4 USD cents/kWh to cover the need to decrease to 6.23 cents USD/kWh to meet the ceiling price requirement from year 11. The economic potential LCOE distribution is shown in Figure 6-4.

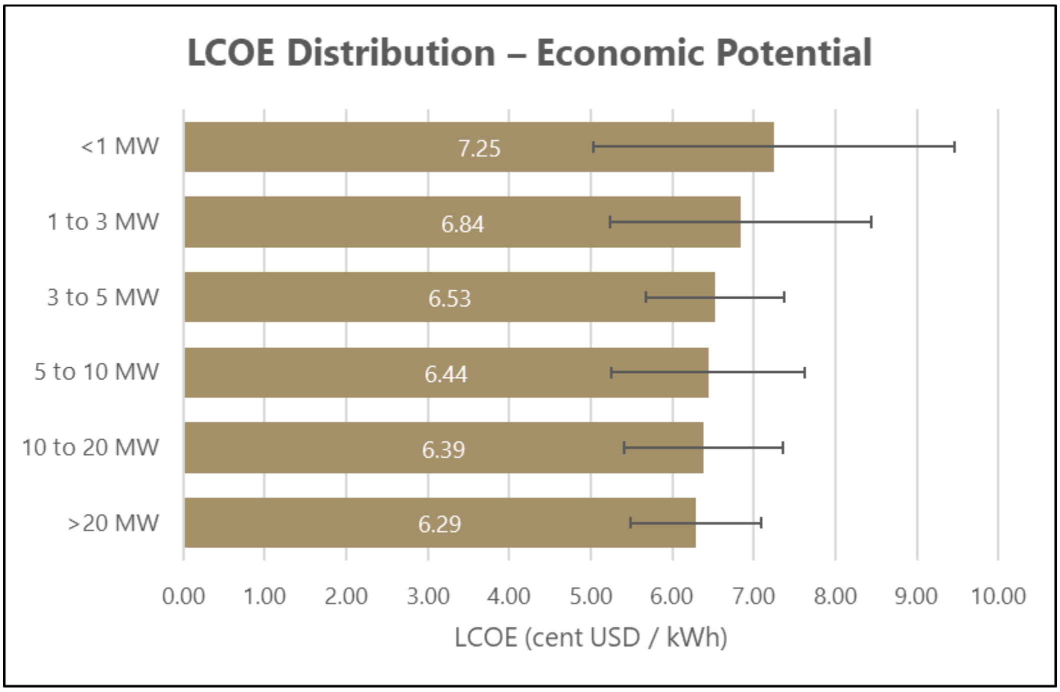

Figure 6-4 Economic Potential LCOE Distributions

As the ceiling prices for a higher capacity become lower as shown in Figure 6-3, the LCOE of FSPV needs to be lower or equal to the ceiling price in order to be considered as having economic potential. The lower LCOE at higher capacity can be achieved through the economic-of-scale deployment of FSPV as shown in Figures 6-3 and 6-4, where the average LCOE is decreased by increasing the installed capacity. However, the LCOE calculation result shows that the decrease rate of LCOE is lower than the rate of ceiling price reduction; thus it becomes more challenging for the water body with a large FSPV to be included in the economic potential due to much lower ceiling prices requirement. For example, all protected lakes are capable of hosting an installed capacity of more than 20 MWp with only 5% water occupancy. However, all the protected lakes' LCOE results are above the ceiling price except Sentani Lake in Papua, and become the other reason why a significant drop in potential is identified as in Figure 6-2.

Figure 6-5 shows the water body's distribution of the economic potential based on its installed capacity potential. The amount of water bodies with an installed capacity of less than 1 MWp is the highest among the size categorizations. The number of economic potential water bodies is decreased when the installed capacity is higher due to the LCOE result at higher capacity generally higher than the ceiling price as explained in the previous paragraphs.

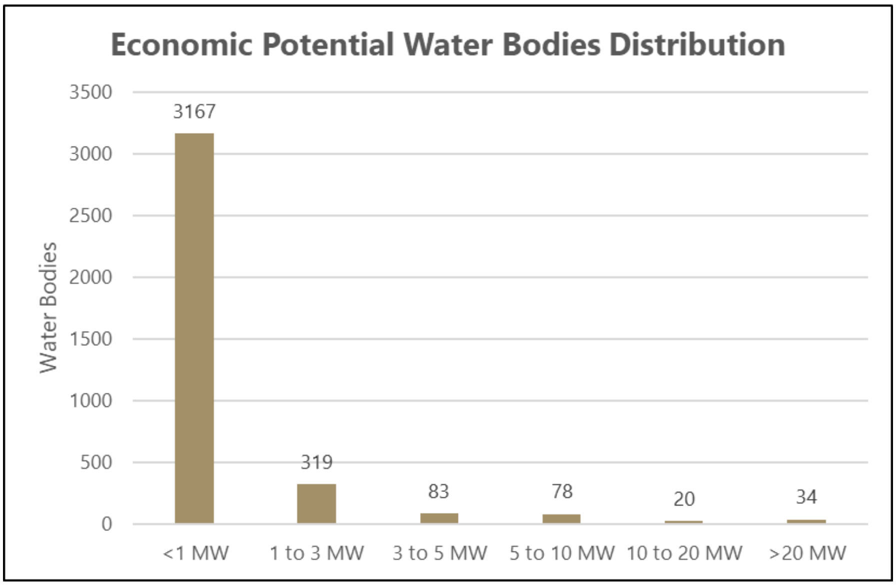

Figure 6-5 Water Bodies Distribution of Economic Potential

A certain insight can be made based on the LCOE result, installed capacity, and ceiling prices. By increasing the installed capacity, the LCOE result will be decreased although at a lower rate compared to the decrease in ceiling prices. Since the location factor also determines the ceiling prices, every province will have a different percentage value drop of installed capacity potential from technical potential to economic potential. Figure 6-6 shows the percentage remaining value from the technical potential result for each province in Indonesia based on the economic potential calculation with 5% water occupancy.

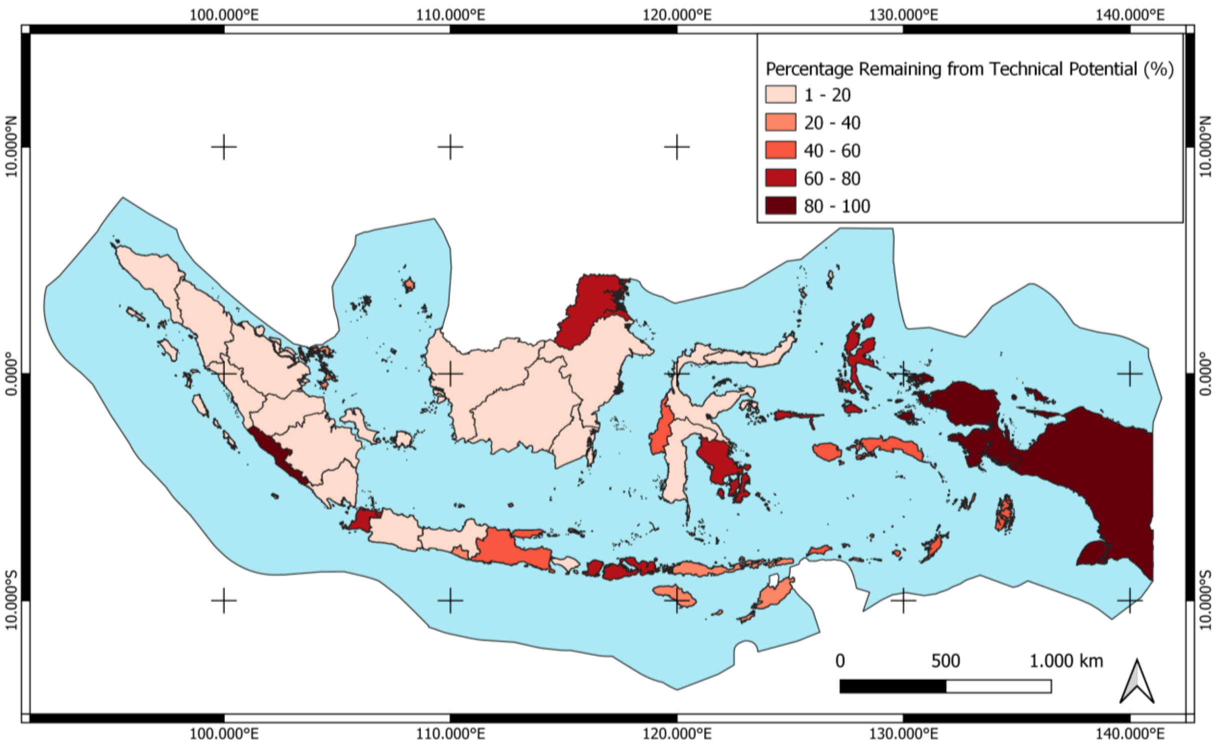

Figure 6-6 Percentage Remaining of Potential from the Technical Potential per Provinces – 5% Water Occupancy

Figure 6-6 helps to understand the impact of different location factors on the ceiling prices calculation and the economic potential. Based on the figure, the remaining potential from technical potential is mainly located in the eastern part of Indonesia although several provinces such as Bengkulu and Banten in the western part of Indonesia still retain a considerable percentage of potential. The eastern part of Indonesia can retain the installed capacity potential during the economic potential calculation due to the higher location factor and ceiling prices compared to the western part of Indonesia. As for Bengkulu and Banten, they can retain a high percentage value of installed capacity potential since those provinces have mostly installed capacity potential with smaller sizes up to 3 MWp per water body. Therefore, higher ceiling prices are applicable for the water bodies compared with the larger capacity in the same location.

However, a lower remaining potential province as in Figure 6-6 does not necessarily mean that it will have lower annual electricity generation compared to the other provinces with a high percentage value. Figure 6-7 shows the spatial results of the economic potential of FSPV annual electricity generation by provinces with 5% water occupancy.

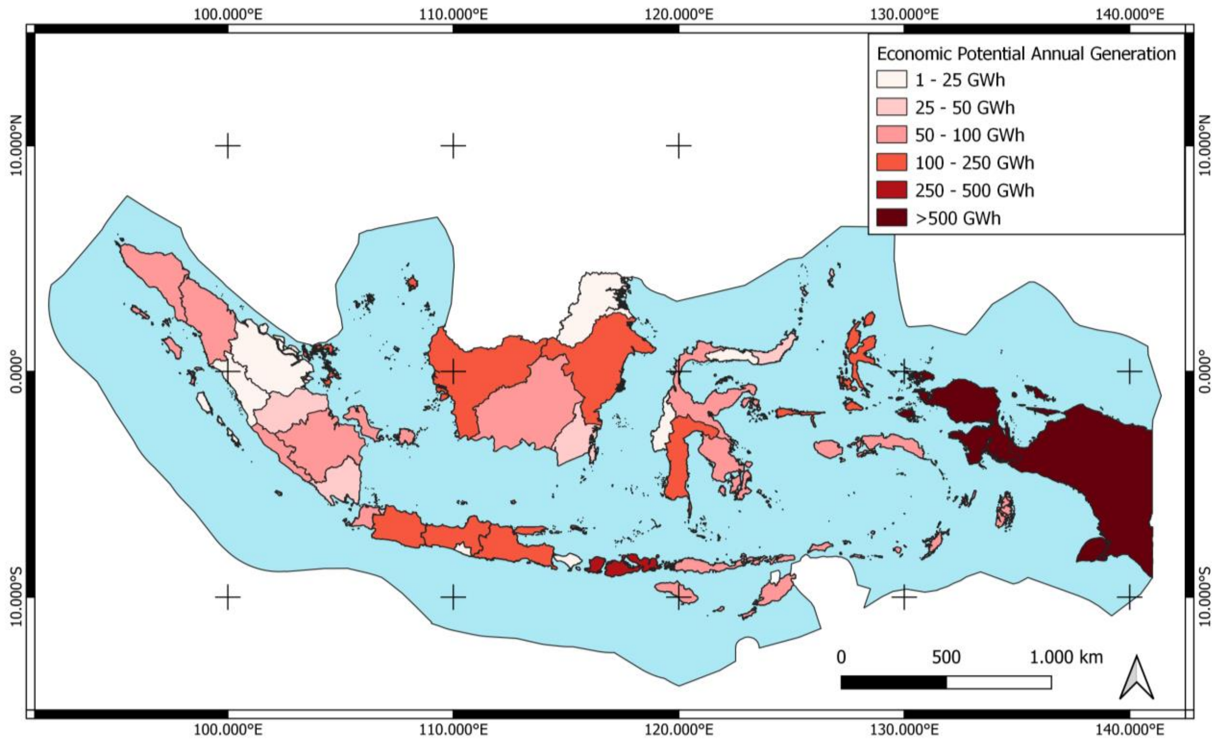

Figure 6-7 Economic Potential Annual Generation – 5% Water Occupancy

As expected, Papua and Papua Barat still have the highest annual generation. It is then followed by Nusa Tenggara Barat. Separately, despite the economic potential in Bengkulu being 94% out of its technical potential, based on Figure 6-7, the province is not one of the largest provinces with annual generation. However, looking at the result from Figures 6-4 and 6-5, multiple factors affect the economic potential of FSPV in Indonesia, namely the location factor and installed capacity categorization in the current ceiling prices regulation. Therefore, it is important to see the effect of changing the ceiling prices as well as a component for LCOE calculations to the economic potential result. This will be further analyzed in Chapter 7.

The LCOE result from this research is also validated using a comparison with other studies. Pinto & Stokkermans (2020) calculated the LCOE of FSPV between 5.03 to 9.62 cents €/kWh at a size of 1 MWp or equal to 5.63 to 10.77 cent USD/kWh using the conversion rate in 2020. Meanwhile, CECP (2022) calculates LCOE between 5.1 to 9.1 cents USD/kWh for Independent Power Producer (IPP) at 160 MWp capacity with the ranges resulting from the different discount rates. A study by Sukarso & Kim (2020) calculated the LCOE of 9.81 cents USD/kWh at 1 MWp in their research in Cirata Reservoir in Indonesia. From the validation check, the result from this study is in a similar range to the other studies. Table 6-1 shows the comparison of LCOE between this research and other studies.

Table 6-1 LCOE Comparison with Other Study

Size	Author Calculation (2022)	Pinto & Stokkermans (2020)	Sukarso & Kim (2020)	CECP (2022)
Up to 1 MWp	5.03 – 9.47 cents USD/kWh	5.03 to 9.62 cents €/kWh	9.81 cents USD/kWh	
>20 MWp	5.48 – 7.09 cents USD/kWh			5.1 to 9.1 cents USD/kWh

6.2 Economic Potential and Demand Coverage Assessment

This section will analyze the economic potential of FSPV in Indonesia in its capability to cover the electricity demand in the country. The capability of economic potential of FSPV in Indonesia to supply the electricity demand will be assessed through a comparison with the latest actual data on electricity consumption per province from Central Agency on Statistics (BPS-Statistics Indonesia, 2022). The information will be retrieved and compared with the annual potential generation of FSPV in the respective provinces. In addition, an assessment of future demand coverage will based on the estimated value from IEA (2022) where an average increase of electricity demand of 4% per year is used. The result of the comparison at 5% water occupancy is shown in Figure 6-8 and 6-9.

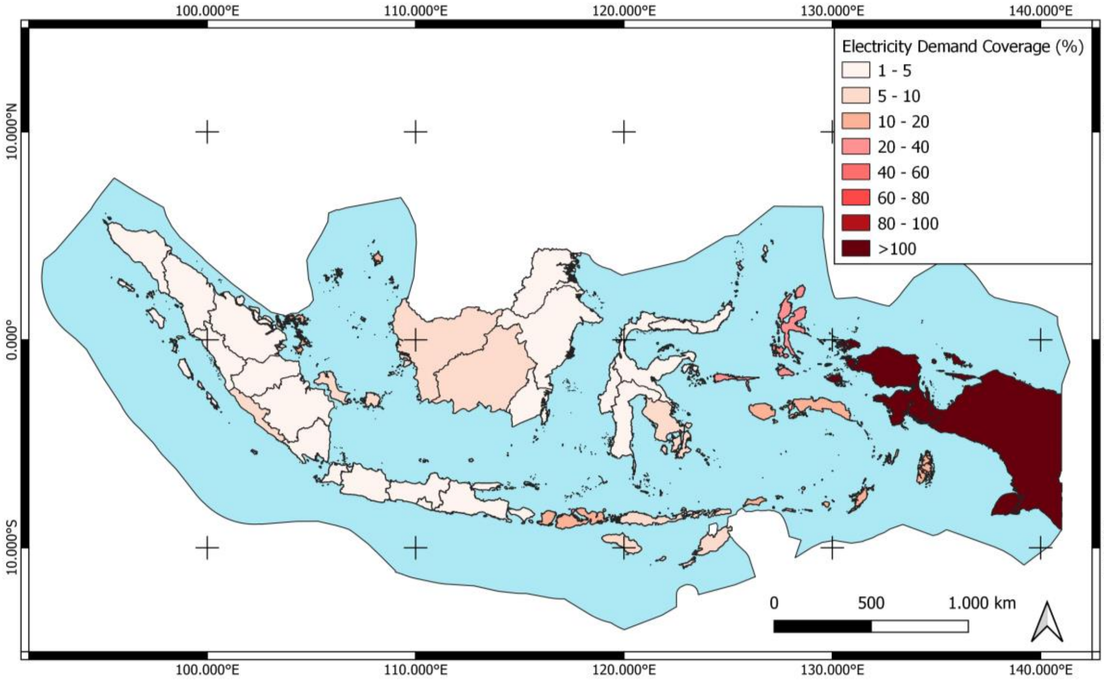

Figure 6-8 Demand Coverage Economic Potential – 5% Water Occupancy (Based on Current Demand)

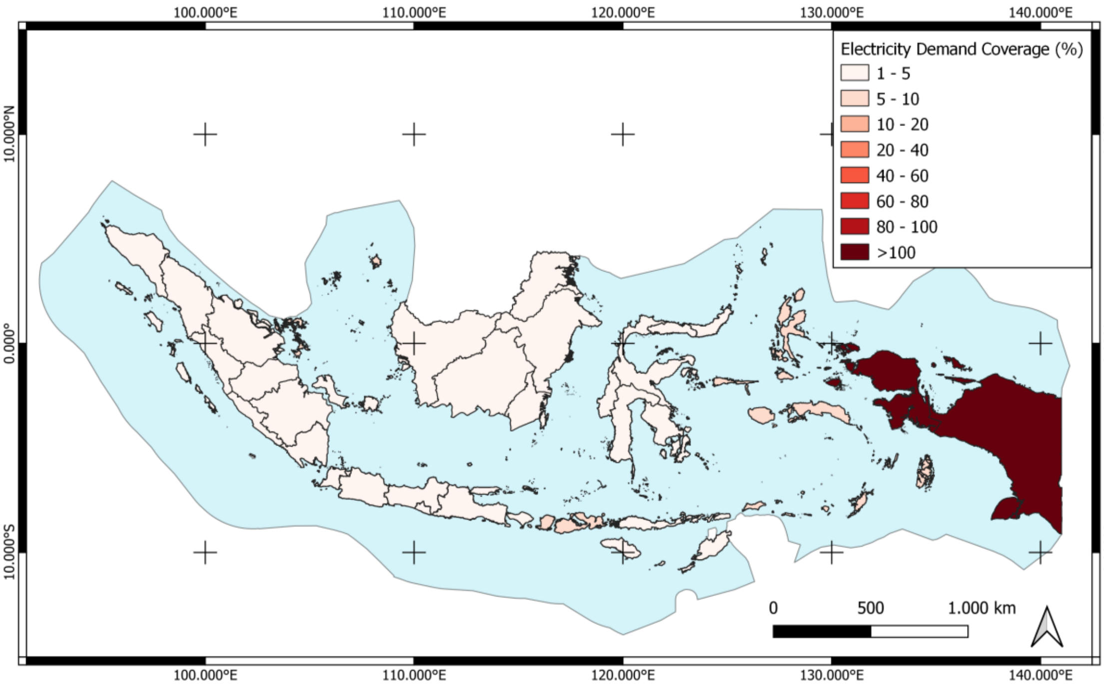

Figure 6-9 Demand Coverage Economic Potential – 5% Water Occupancy (Based on 2030 Projected Demand)

Based on Figure 6-8, the annual electricity generation from the FSPV plant is only able to supply less than 5% demand coverage in most provinces in Indonesia with a total amount of 22 provinces. Meanwhile, there are six provinces with 5 to 10% demand coverage. The other six provinces can meet the electricity demand of more than 10%. However, FSPV can supply more electricity than its demand in Papua and Papua Barat. If the comparison is based on 2030 projected demand as in Figure 6-9, the demand coverage become less due to the growth of the electricity demand. It is however, Papua and Papua Barat is still able to supply more than the electricity demand in 2030. Details of the demand coverage of every province are shown in Appendix C.

Further analysis is performed for the demand coverage based on per-province identification. It is identified that the highest electricity demand coverage is generally identified in the eastern part of Indonesia, while the lowest electricity demand coverage is in Java and Bali. This is because the population of Indonesia is concentrated in the western part of Indonesia, especially Java. With the combination of not so much installed capacity potential in the region, thus the demand coverage is low in these areas. In opposite, the eastern part of Indonesia is a less dense population compared to the western regions. However, with higher installed capacity potential, a higher demand coverage is possible in this region where the annual generation potential is higher than the electricity demand.

7 Sensitivity Analysis and Support Schemes

This chapter aims to present the sensitivity results of the LCOE calculation to the changes of economic potential as well as to provide set of recommendation support schemes to increase the economic potential. Section 7.1 shows the sensitivity results of FSPV based on the selected scenarios. Section 7.2 examines the policy and scheme in other countries. Meanwhile, section 7.3 provides the current policy and regulation that is related to the FSPV and energy sector in Indonesia. Section 7.4 discusses the recommended support schemes that can be adopted by the stakeholders.

7.1 Sensitivity Results

Sensitivity analysis is used to determine how sensitive the LCOE is and subsequently the economic potential result of FSPV in Indonesia in key variables such as capital expenditures, operational expenditures, discount rate, and applicable ceiling prices. It is also used to help to understand which component has a significant impact on increasing the economic potential of FSPV in Indonesia. The analysis also helps to understand which support schemes that have a significant impact on increasing economic potential.

The scenarios selected for sensitivity analysis are based on Table 3-11 in Chapter 3. First, the changes in capital costs, operational costs, and discount rates to the LCOE and economic potential are calculated. The variation of the LCOE and economic potential results from the variation of each parameter by ±10% relative to the base LCOE value of 6.76 cent US$/kWh while it is 6,401 MWp for the economic potential. The base LCOE value is based on the average LCOE result. The sensitivity result of these scenarios is shown in Figure 7-1 and 7-2.

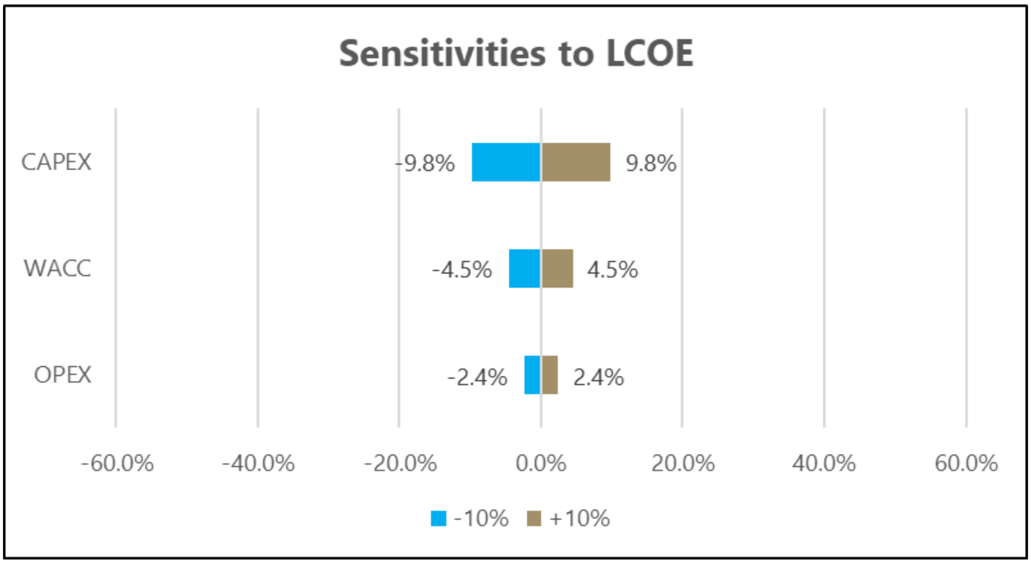

Figure 7-1 FSPV System Sensitivities to LCOE

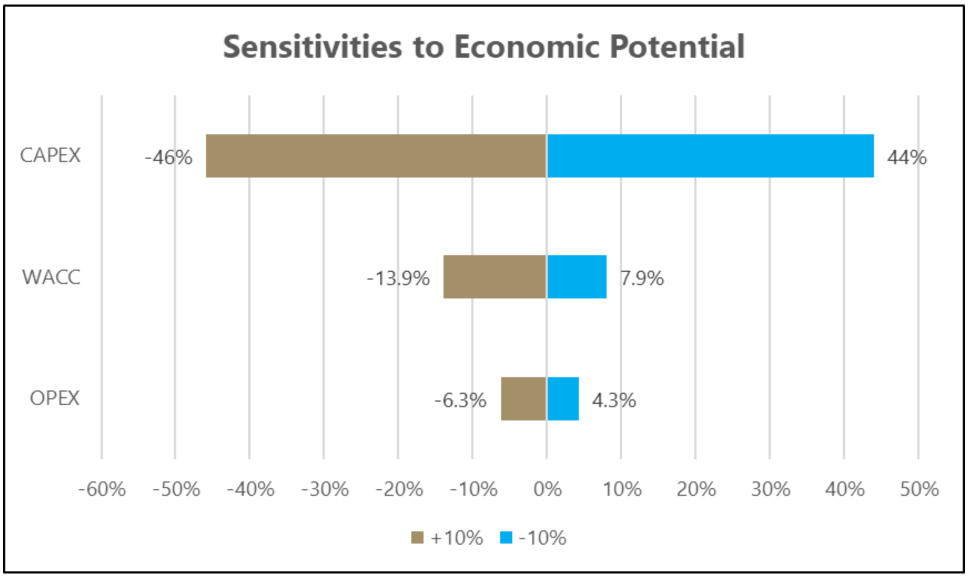

Figure 7-2 FSPV System Sensitivities to Economic Potential

Based on Figures 7-1 and 7-2, a decrease in CAPEX has the highest impact on increasing economic potential, followed by discount rate and OPEX. It is also identified that the variation of 10% value to the base case value of economic potential leads to a different figure of a percentage value. The results show that a slight change in LCOE has a relatively high impact on economic potential. For example, an increase of 10% in CAPEX value will increase the LCOE by 9.8%. However, an increase of 9.8% in LCOE leads to a decrease in economic potential by 46%. This implies that there are water bodies with a base case value of LCOE that is slightly above or below the ceiling prices, thus quite sensitive to the economic potential if there are any changes in the LCOE. No linearity is identified between the changes in LCOE to the economic potential since the economic potential requires ceiling prices as its indicator. For example, a decrease of 9.8% of LCOE in Java Island may still not be included in the economic potential if it still cannot meet the ceiling price requirement. The sensitivity analysis then continues to the other aspect of indicators for economic potential: ceiling prices and possible cost reduction of FSPV in 2030. The ceiling prices are increased by 10%, while the estimated capital cost reduction of solar PV is 30%. The result of these cases is shown in Figure 7-3.

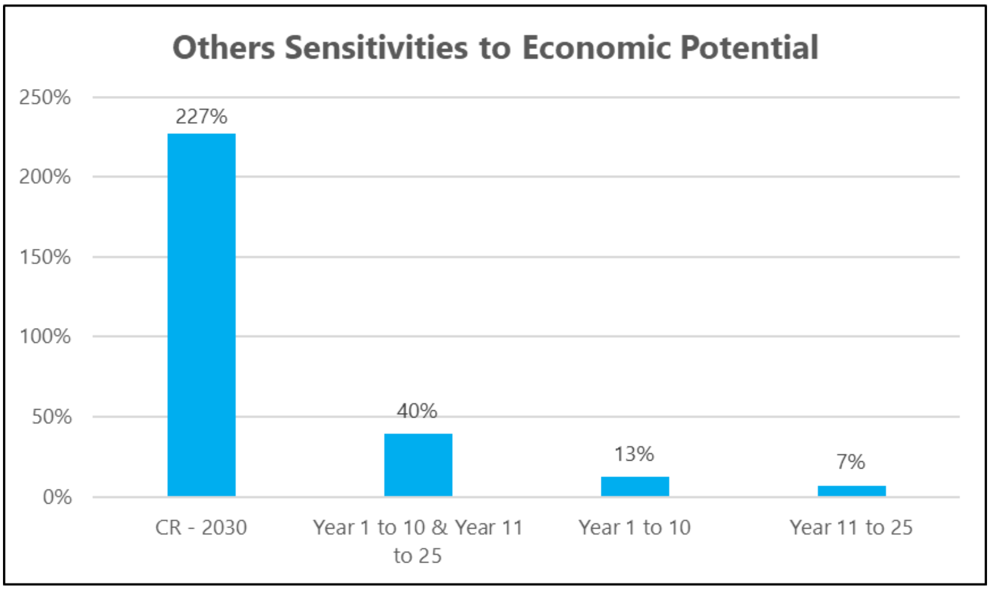

Figure 7-3 Other Sensitivities to Economic Potential

The result shows that an increase in both ceiling prices year has the highest impact on increasing economic potential compared to an individual increase in ceiling price year. The individual increase in ceiling price has less impact on the economic potential with the changes in Year 1 to 10 leads to a slightly higher increase in the economic potential compared to changes in Year 11 to 25. A higher increase in economic potential by increasing the ceiling prices in Year 1 to 10 is identified due to the application of the discounting value for the LCOE calculation. Even though both Year 1 to 10 and Year 11 to 25 ceiling prices are increased by 10%, the application of discounting leads to a lower value for the electricity prices in Year 11 to 25 which turns out to be impacting the changes in the economic potential. This result can be treated that increasing the ceiling price in the first ten years has more impact in the long term rather than increasing the ceiling price for later years.

It is also identified that there are water bodies with location factor of 1.1 or more that have calculated LCOE slightly lower than ceiling price in years 1 to 10 but will not be considered as economic potential unless there is an increase in both ceiling prices year. For example, there is a water body with a potential installed capacity of 11.8 MWp and a calculated LCOE of 6.86 cents USD/kWh in Kalimantan Barat. Since the applicable ceiling prices for this location are 8.29 for years 1 to 10 and 4.97 cents USD/kWh from year 11, it cannot be included in the economic potential even though the effective LCOE value is maximized to 8.29 cents USD/kWh for the first ten years in order to minimize the cost from year 11. The water body will be only included in the economic potential if both applicable ceiling prices are increased by 10%.

Separately, if the cost reduction of FSPV in 2030 follows the same path as in Graham et al. (2022) from CSIRO, a significant increase in economic potential is identified. However, as the energy transition is required to address the challenges of climate change and energy security, an immediate support scheme for FSPV might be required.

7.2 Policy and Scheme in Other Countries

The policy and implemented support schemes of the other countries can be a reliable reference, especially with the country that already has a deployment of floating solar. As per data from World Bank Group, ESMAP, and SERIS (2019), China is the largest country with the most installed FSPV capacity in the world followed by Japan and the Republic of Korea as shown in Figure 7-3.

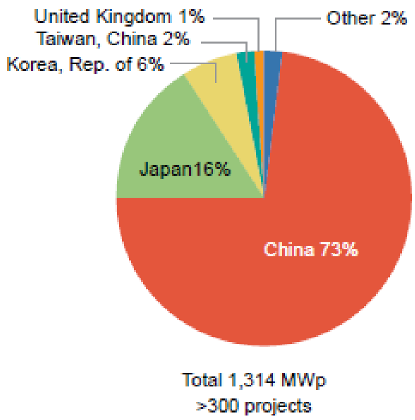

Figure 7-4 Global Installed Capacity Distribution of FSPV in 2018 (World Bank Group, ESMAP, and SERIS, 2019)

Based on Figure 7-4, the development of FSPV takes place more in the Asia continent while there is a minor portion from other countries such as the United Kingdom. However, as the latest data from the World Bank Group, ESMAP, and SERIS (2019) is based on 2018 and may be outdated, updating this information is required considering that there is a development of FSPV in other countries such as the Netherlands and India. For example, The Netherlands already has an installed capacity of around 211

MWp as of 2021, mostly online in 2021 (Weetch, 2021; Groenleven, n.d.). Meanwhile, India has an installed capacity of around 170 MWp and around 1.8 GWp under development (Gopal, 2022).

Gadzanku et al. (2021) surveyed the incentives and policies already implemented in the countries shown in Figure 7-3. First, China has programs to support PV deployment in the country, such as PV Build Plan, PV Top Runner Program, and national and regional targets. PV Build Plan is a feed-in-tariff program to encourage the development of PV in China through a guaranteed higher electricity price than the market rate for electricity with a value of up to 0.128 USD/kWh (Lin, 2019). PV Top Runner Program requires the developer to use a certain minimum PV performance, such as on module efficiency. Meanwhile, the national and regional targets are similar to the national electricity plan in Indonesia, which set a target deployment of solar PV in a specific location.

Japan also used a support mechanism in the form of a feed-in tariff with a guaranteed value of up to 0.19 USD/kWh. However, this is being gradually phased out to minimize the financial cost burden of the government (Enerdata, 2020). Moreover, financial institutions in Japan also provide loan support for solar PV development.

The Republic of Korea provides another example of a support scheme for solar PV. The country has consistent financial support for the research and development of FSPV from the initial phase of research up until a pilot project. Moreover, the country also has Renewable Portfolio Standards (RPS) that are used to assign a requirement of minimum renewable energy generation through a Renewable Energy Certificate (REC) in the industry with a specific weight factor for FSPV as well. However, there is no specific requirement for achieving the minimum renewable energy generation and certificate. Since the certificate is issued based on the calculation of the weight factor and the electricity generated from the renewable plant, the industry can select which type of renewable energy they will deploy. The applicable weight factor for FSPV is higher than the weight factor for ground-mounted PV. Thus the industry can achieve the certificate target easier by using FSPV for the same electricity generation. However, if the industry is not able to meet the requirement, there is a penalty for the industry, and it will be increased if there is frequent non-compliance (Korea Energy Agency, n.d.).

Taiwan also followed the same approach used in Japan and China with feed-in-tariff schemes. However, the difference with the other two countries is that Taiwan has a higher feed-in tariff of 0.14 USD/kWh for FSPV than the other type of solar PV (Bellini, 2022). As Gadzanku et al. (2021) mentioned, using this specific feed-in tariff, the country's FSPV deployment is increased by 30% within the first nine months of the implementation.

The Netherlands has a subsidy mechanism to support renewable energy deployment in the country through the Sustainable Energy Production Incentive (SDE++). The financial support will be re-calculated every year and depends on the amount of electricity produced by FSPV. There is a maximum rate of subsidy for FSPV, which can be up to 0.0705 €/kWh (RVO, 2022). The subsidy for FSPV is higher than the land-based. However, the country also has another approach to support the FSPV deployment by creating a consortium between the companies, research institutions, municipalities, and universities. This consortium has an agenda to achieve a larger realization of FSPV in the country by sharing knowledge of the nascent technology of floating solar.

India also has support mechanisms in the country for solar PV by means of financial support, namely Central Finance Assistance (CFA) and Viability Gap Funding (VGF) (Ministry of New and Renewable Energy, n.d.). Central Finance Assistance is support for solar PV through financial provisions specific to the capital expenditures of solar PV projects. Meanwhile, Viability Gap Funding is a program similar to the Central Finance Assistance. However, there is a difference in the amount of capital cost support per MWp between the programs, with the VGF able to provide a higher amount of financial support but requiring a higher requirement, such as meeting a minimum local content requirement in the solar PV project in order to be eligible for the support. The country also provides tax incentives for FSPV in the form of custom duty exemptions and income tax exemptions (Gupta, 2021).

Lastly, although the United States is not part of the largest FSPV deployment in the world, one of the states in the country, Massachusetts, provides an interesting lesson for support schemes of FSPV. There is a financial incentive of 0.03 USD/kWh for the FSPV if the proposed project is located in a specific water body with minimum water quality impacts if FSPV is laid on the water surface and maximum water occupancy coverage of 50% (Gadzanku et al., 2021).

Overall, most of the countries that are reviewed above provide support in the form of feed-in tariffs to increase solar PV development. There is also another means of support through using knowledge sharing in the form of a consortium, capital costs incentives, tax incentives, and target requirements with a penalty. Republic of Korea, Taiwan, the Netherlands, and the United States are the countries where specific support or criteria is assigned for FSPV, while China, Japan, and India provide support for solar PV in general regardless it is ground-mounted or floating solar.

7.3 Current Policy and Regulation

Finding the current implemented policy and regulations related to the floating solar development in Indonesia is required before creating any recommendations to increasing the economic potential of FSPV in Indonesia. Four regulations are identified that relate to solar PV or floating solar. First, the water occupancy requirements as stipulated in PERMENPUPR/No.27/PRT/M/2015, limit the occupancy of floating solar up to 5% water occupancy. This limitation forms the basis of deciding factor of the technical potential in this study. Second, 7 water bodies are listed in the national electricity plan or RUPTL 2021 – 2030 with a total capacity of up to 612 MWp. The national electricity plan specified which water bodies and the size of the installed capacity of the FSPV. However, these potential FSPV projects do not yet have a target completion date, unlike other renewable energy forms such as geothermal, hydro, and land-based solar PV. Since there are only 7 water bodies with a total capacity of up to 612 MWp as listed in the national electricity plan, the result from this study can strengthen the knowledge and information required to develop the FSPV in Indonesia further. Third, the solar PV ceiling prices, as defined in PP No.12/2022, are also part of the economic potential indicator. Finally, the minimum local content requirements of solar PV projects, as stipulated in PERMENPERIND/4/2017, limit the selection of PV modules and other components for the FSPV project to meet the domestic content percentage.

Exploration of current policy and regulation in Indonesia is also performed on a larger scale and timeframe. It was identified that a feed-in tariff for solar PV was shortly introduced in the country in 2013. The scheme was implemented based on the local content percentage, with a higher local content resulting in a higher guaranteed price (Devine et al., 2015). However, this was later revoked by the Supreme Court due to the legal action initiated by the local solar panel association that highlighted that the scheme provides the possibility of using imported panels. At the same time, the Indonesian Law No.3 of 1984 on Industry requires the use of prioritization of local products. Another challenge identified is the Build Own Operate Transfer (BOOT) rules that require any developer that builds any electricity project to transfer all the assets to PLN at the end of the contract (Hamdi, 2019). This further creates a challenge for developers to recoup their investments with a limited contract period and without a feed-in-tariff scheme while also needing to meet the local content (Hamdi, 2019).

A review of the support mechanism of the competing technology is also performed. Coal-fired power plants dominate the electricity market landscape in Indonesia thus analysis of these competing technologies is required. A report by the International Institute of Sustainable Development (IISD) (2019) and their report from 2017 are used since the report already summarized all of the supporting mechanisms for coal. The report provides the list of support schemes for coal-fired power generation with a quantified value for several forms of schemes as well as the list of schemes without a quantified value.

First, a loan credit by the government for a coal-fired power plant project is identified for US$47 million to US$70 million from 2012 to 2016 which can vary depends on the number of new coal-fired power project. The largest amount of the quantified value schemes in the report is mainly on the type of revenue foregone for the government. Tax exemption and reduced value-added tax rate on goods and services are the largest quantified schemes for the type of government revenue foregone with the calculated amount between US$562 million and US$766 million. Although it may varies per year, the government will have a yearly revenue foregone as long as the tax exemption and reduced value-added tax mechanism is still in place.

There are also other types of support schemes without the yearly quantified funding support. The country provides loans for coal-related projects, for example, for the Batang coal-power plant project in the amount of US$33.9 million. However, the total yearly amount is not specified in the report. Meanwhile, there are schemes without quantified value that leads to revenue foregone such as reduction in the yearly corporate tax rate and value-added tax exemption on purchases of coal by coal consumers, although it varies according to the contract.

The government also provided yearly financial support of an average US$6.7 million for the research and development of coal-related research. Moreover, there is a yearly electricity subsidy to reduce the household tariff, which varies per year. This tariff subsidy does not distinguish the sources of electricity. For example, there is amount of US$51 million for electricity subsidies for households in 2019 (Cindy, 2020). Nevertheless, there are various forms of support for coal-fired power plants with and without direct funding. The estimated amount in the report from IISD is around US$700 million per year and can be even higher if it includes non-quantified support schemes (IISD, 2019).

The government also has a 35 GW program to boost the country's electricity generation, which originally targeted an additional 22 GW of coal power plants and later was revised to 13 GW to avoid any possibility of oversupply. The program received funding from the private entity as well as the government in the amount of US$26 billion, although there is no specific funding amount by the government mentioned in the report (IISD, 2019). In addition, the coal-fired power targets of 13 GW alone are already a significant amount compared to the 612 MWp of planned FSPV in the national electricity plan. An important step was taken in 2022 as the government announced that the coal-fired power plant would be imposed carbon taxes of about US$2 per ton of carbon (Mapa, 2022). However, in the same year, Indonesia also announced that the carbon tax scheme for coal-fired power generation would be delayed indefinitely.

A simple approach to calculate the impact of the support to the coal-fired power plant and use it to support the FSPV development is performed in this study. Using the electricity generated by the coal-fired power plant of 180,689 GWh from IEA (2020), a CO_2 tax of US$2 per ton, and yearly CO_2 emissions of 0.755 kg/kWh (IISD, 2019), a CO_2 tax revenue of US$286 million could be possible. If all of the CO_2 tax revenue is used for the 10% capital support incentive of FSPV, this amount will be able to support 3,770 MWp of FSPV. Meanwhile, if the government funding and revenue foregone of US$700 million are used to provide an incentive of 10% of capital expenditure, this amount will be able to support 9,210 MWp. Both of these values are more than enough to increase the economic potential of FSPV in Indonesia since the result from sensitivity analysis provides that by reducing 10% of capital expenditure, the economic potential of FSPV will increase by 44% or 2,817 MWp.

7.4 Recommended Support Schemes

Based on the findings of the sensitivity analysis, other countries' support schemes, and the current regulations in Indonesia, it is recommended that stakeholders adopt supportive schemes to encourage the widespread adoption of FSPV in Indonesia to increase economic potential. There are several identified support schemes, such as capital expenditure incentives, feed-in tariffs, and re-evaluation of the ceiling prices. Although feed-in tariff and ceiling prices might be similar, it is two different types of schemes. The feed-in tariff is for providing guaranteed and predictable revenue by the power producer, while the ceiling price is for limiting the financial burden on the household consumers, although the government can partially subsidize it to keep the price of household electricity. In addition, feed-in tariffs could be higher than ceiling prices.

Additionally, more relaxed requirements for receiving loan financing is another way to increase economic potential. Hamdi (2019) identified that international bank requires a certain minimum project size and portfolio experience in order to receive the loan. However, a support from the government-owned bank with a lower interest rate or relaxed requirements compared to the international bank can be the alternative to the foreign bank. The implementation of a CO_2 tax is also an alternative solution to increase economic potential by using the revenue to support the FSPV development. A training program for the local workforce is another way to minimize operational costs. Practitioners and companies in the solar industry can collaborate through a consortium to identify best practices for ensuring the successful adoption of FSPV in Indonesia.

A target requirement for the installed capacity of FSPVs with a penalty for not meeting the target for specific industries or locations can also be the other scheme to boost the FSPV installation. For example, a requirement to use a renewable energy source at certain amount of electricity consumption in large-scale factory will incentivizes the factory to develop its own FSPV at its water reservoir. Finally, a consideration in increasing the allowable water occupancy can be a solution to increase the economic potential. Table 7-1 shows the summary of the identified support schemes to increase the economic potential of FSPV in Indonesia.

Table 7-1 Summary of Identified Support Schemes

Schemes	Description
Capital Expenditure Fiscal Incentive	Provide capital support i.e., certain $ per Wp or maximum certain percentage of total installed cost based on certain factors (location, local content, capacity).
Feed-in-Tariff	Provide guaranteed electricity price per kWh based on certain factors (location, local content, capacity).
Re-evaluate the Ceiling Prices	Re-evaluate the latest ceiling price mechanism for example on the value assigned for the first 10 years.
Utilization of CO_2 Tax for FSPV Development	Once the carbon tax is in place, the tax revenue is used for fiscal support of floating solar PV.
Workforce Development	Provide training and education on Floating Solar PV to utilize local labor.
FSPV Portfolio	Consider implementing minimum requirements installed capacity of FSPV for specific sectors / industries / locations with penalty.
National Consortium	The consortium to initiate discussion, R&D, pilot/demonstration project, policy recommendations related to FSPV.

Schemes	Description
Loan Financing	Support from local and/or international banks for FSPV financing with more relax requirements and lower interest rates.
Water Occupancy	Increase maximum water occupancy through general percentage cap or different cap based on water quality

Although nine support schemes are identified in this study, three sets of support schemes require more attention and consideration for the stakeholders with a priority level. The first priority scheme is by increasing the current maximum allowable water occupancy in the regulation or using a similar mechanism implemented in Spain that deploys different water occupancy based on water quality in the water body. This mechanism virtually requires no financial support from the government, and there is a precedent of higher water occupancy in other countries, such as Spain with water occupancy of up to 20% and in the United States up to 50%. As calculated in Chapter 6, increasing the water occupancy only to 10% can increase the economic potential by around 6 GWp and even can be up to 39 GWp if the water occupancy is 40%.

Second, the Capital Expenditure Fiscal Incentive mechanism is another scheme that is able to increase economic potential. As Indonesia also wants to prioritize its domestic content, the financial support amount can also be differs based on the local content. The sensitivity analysis shows that reducing capital costs by 10% could increase the economic potential by 2.8 GWp. This thought can be achieved by providing financial support of around US$215 million. The advantage of this mechanism is that the financial support does not require a yearly budget of US$215 million from the government as it is targeted for capital costs. In addition, the budget can also be spread over several years and can be gradually phased out. Separately, this budget can also be achieved by using carbon tax from coal-fired power plants once it is in place.

Lastly, the support schemes on the contracted price, either through increasing the ceiling prices for the first ten years or providing a feed-in tariff, could be the other alternative solution to increase the economic potential of FSPV. The sensitivity analysis shows that increasing the ceiling price of the first ten years could increase the economic potential by 0.8 GWp. However, this mechanism implementation requires a yearly commitment, thus leading to higher fiscal support in the long term. If all of FSPV's economic potential at 5% water occupancy is being built without implementing support schemes, the yearly budget for purchasing electricity could be up to US$565 million for the first ten years. Then, suppose there is a support mechanism implemented for the first ten years by increasing the ceiling prices. In that case, the government needs to set aside an additional yearly budget of up to US$65 million if using a feed-in tariff mechanism. This scheme, either using a feed-in tariff or increasing the ceiling prices, becomes the last priority due to the need for yearly commitment to maintaining the guaranteed price in the case of a feed-in tariff or financial burden increase by the household in case of an increased in ceiling prices if not subsidized by the government.

Based on the review of the three priorities of recommended support schemes, there are two scenarios that the government could adopt. First, by combining the increased water occupancy regulation and capital expenditure incentive. The second is through a combination of the increased water occupancy and feed-in tariff or increased ceiling prices with a subsidy from the government. The first scenario is the preferable solution due to minimizing the potential financial burden by the government but able to increase the economic potential more than the second scenario.

7.5 Scenario to Increase the Economic Potential

The scenario based on the combination of increased water occupancy and incentive support for the capital expenditure is selected to show that there is a potential to achieve the country's target on the energy transition. The report from IEA (2022) stated that the installed capacity target of solar PV in Indonesia by 2030 is around 20 GWp. Since the information also received suggestions from Indonesian stakeholders, thus it can become a starting point for creating the scenario. The report, however, does not classify which type of solar PV that is targeted to be installed in 2030.

Since there is no detailed yearly plan of the cumulative installed capacity target in the report by IEA (2022), this study will provide a scenario for reaching the 2030 target. Several key assumptions must be made to create a yearly plan scenario. First, the start year of 2023 is used with a cumulative installed capacity of solar PV of 356 MWp. This consists of the existing installed capacity of solar PV of 211 MWp from Statista (2022) and the expected operation date of 145 MWp Cirata FSPV by the end of 2023. Second, there is a constraint on the domestic solar module production capacity of 580 MWp per year, limiting the possible yearly installed capacity (Rahayu, 2023). This constraint is used to meet the local content requirements in solar PV projects in Indonesia. Third, an assumption of yearly capital cost reductions from Graham et al. (2022) is used. Thus, it will affect the economic potential value of FSPV as it will be used in the LCOE calculation.

A business-as-usual scenario is defined to understand whether the current conditions in Indonesia and without any support schemes are able to create the possibility of reaching the target of 20 GWp in 2030. Assuming the yearly installed capacity of FSPV is added by 580 MWp, which is based on the full production capacity of domestic production, a total of 4.4 GWp installed capacity is estimated by the end of 2030. With the target of 20 GWp in 2030, a business-as-usual scenario virtually cannot achieve this target unless specific measures are implemented in Indonesia.

Therefore, support is required in solar module production to meet the local content requirements and reach the 20 GWp targets by 2030. As a reference, the construction of a 3 GWp factory requires around two years before starting production (Enel, 2022). In addition, an investment of around US$800 million for a 3 GWp solar factory is required (Dehghanimadvar et al., 2022). The investment in the new production facility is needed as soon as possible, with the expectation of the start of operation in 2026.

Separately, a more relaxed local content requirement needs to be adopted in the years when the new solar production facility is being constructed. This can be in the form of allowing a solar import module with the amount of import product capacity not more than the yearly capacity of domestic capability, which is 580 MWp. A yearly combination of local and import products will be 1,160 MWp. After the completion of the new production facility, this support by allowing the import of products can be abolished as the country is expected to have a larger yearly production capacity which is 3,580 MWp.

Since this scenario involves increased water occupancy and capital incentive support schemes, this support is required when the new production capacity is online. This is because at a larger production capacity, there will be a particular point of additional capacity of FSPV where it is no longer economic potential after all of the economic potential locations already installed in the previous years. Therefore, these support schemes are introduced in the year when the new solar module production facility is online. Figure 7-5 shows the yearly planning of the target installed capacity and when specific support is required.

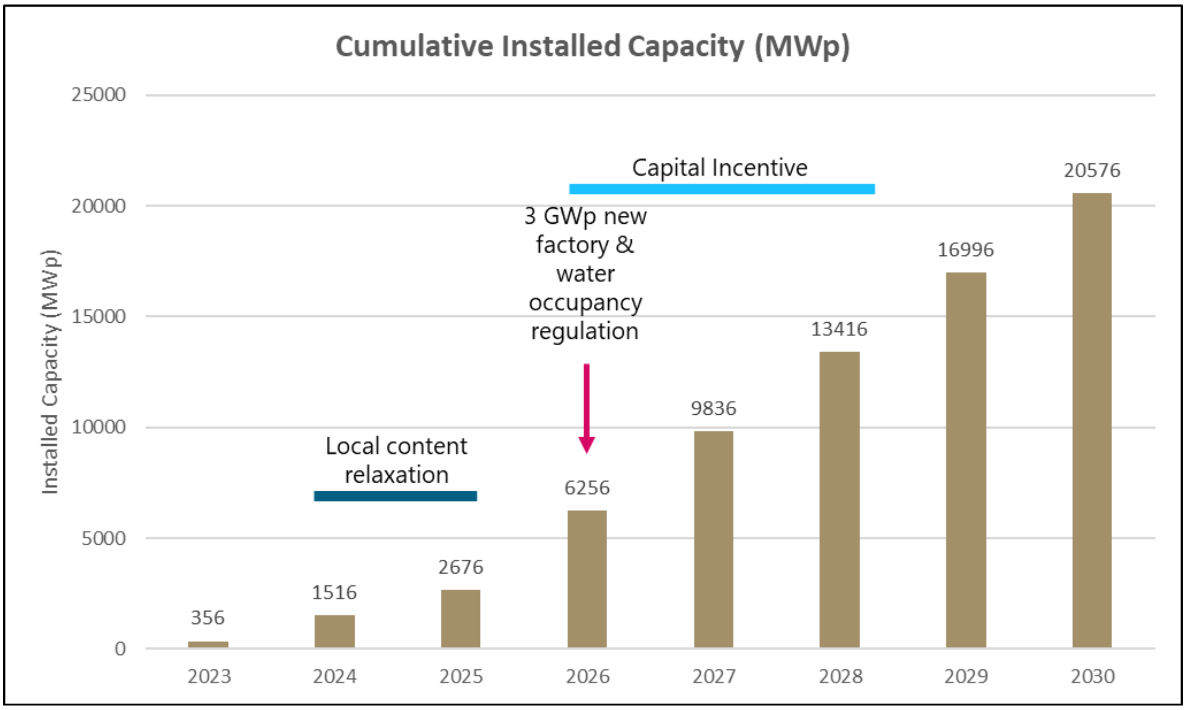

Figure 7-5 Scenario to Achieve 2030 Target of Installed Capacity

Based on Figure 7-5, if the country provides a relaxed local content requirement in 2024 and 2025 while constructing a large-scale solar production facility, Indonesia can fully source its solar module locally starting in 2026 and meet the 2030 installed capacity target. In addition, an update of the water occupancy regulation to 10% will help to meet this target together with a 3-year program of capital incentives. This capital incentive package is targeted only from 2026 to 2028 with an amount program of US$215 million, spread evenly throughout the years. It is assumed that starting in 2029, the country is no longer required to provide specific capital incentives due to the expected cost reduction from Graham et al. (2022). With this scenario, it is estimated that the country will be able to meet the 20 GWp target of solar PV by 2030 in the form of floating solar.

8 Discussions

After the result findings and analysis of each aspect of the research questions in the previous chapters, this chapter will discuss the author's view on the literature review, methodology, and results finding in section 8.1. The limitations of the study will be presented in section 8.2.

8.1 Discussion on Research

This discussion section will discuss the experiences and perspectives related to the study on floating solar PV potential in Indonesia. This thesis aims to investigate the technical potential and economic potential of FSPV deployment in Indonesia while also identifying ways to increase the economic potential for widespread adoption. Therefore, this section will discuss the research journey from literature review, methodology selection, and the result of this research.

8.1.1 Literature Review Discussion

The purpose of the literature review in this study is to evaluate the existing literature on floating solar PV. Through the literature review, it is found that there is a significant academic knowledge gap in floating solar PV compared to ground-mounted solar PV or rooftop solar PV, especially in Indonesia. Therefore, the effort of the literature review is expanded to include the literature about FSPV outside Indonesia.

It is found that the research about FSPV at the national level in Indonesia with detail on technical potential and economic potential is currently unavailable. Literature review in a broader location provides more understanding of the technical, economic, and environmental considerations associated with the FSPV. Regarding technical potential, the research from Lopes et al. (2022) becomes the foundation of this study since the research follows a similar methodology of identifying technical potential in a country using QGIS. As for economic potential, the literature review provided ways to identify an economic potential for FSPV and how to increase it. However, based on the literature review, it also had areas that should be addressed in future research, such as on calculation model for floating solar PV, while this research study tries to provide scientific contribution in the areas of site selection, technical potential, and economic potential of FSPV.

In terms of scientific contribution, this study provides reasoning and a review of each criterion that is previously unavailable or only briefly discussed in the existing literature. Meanwhile, as the only available study that provides a quantitative figure of FSPV potential in Indonesia is from Silalahi et al. (2021) with a theoretical potential amount of 50 GWp at 5% water occupancy, this research is able to provide the technical potential of FSPV in Indonesia with a potential installed capacity of 33.4 GWp at 5% water occupancy. The result from this study is more relevant and can be helpful for future studies since it is already considering technical constraints such as FSPV system arrangements and design limitations. Moreover, this study also provides the economic potential of 6.6 GWp at 5% water occupancy in Indonesia, which already considered the country's economic constraint, such as the maximum electricity purchase price. Therefore, this study contributes to floating solar in general by providing a detailed analysis of site selection criteria, especially in Indonesia, by showing the technical and economic potential of FSPV deployment in the country.

8.1.2 Methodology Discussion

Since this research aimed to investigate the technical and economic potential of FSPV in Indonesia, a combination of quantitative and qualitative analysis is capable of helping to understand the feasibility of implementing FSPV in Indonesia. Developing the selection criteria for site suitability of FSPV creates a deep understanding of the impact of each possible criterion on the FSPV deployment. However, it can be expanded if field collection data is used for site suitability assessment. The use of QGIS and the datasets used in this research enabled this study to show the technical and economic potential. Because there is still no firm and widely recognized model for calculating the electricity generation for FSPV, the use of three methods to calculate the technical potential helps to understand the effect of each parameter on the energy output from FSPV and the potential of the cooling effect in FSPV.

The LCOE method and comparison with the ceiling prices in Indonesia provided a framework for evaluating the economic potential of FSPV in Indonesia. Meanwhile, sensitivity analysis helps address the impact of ceiling prices on the economic potential and derive insights into the changes in economic potential upon a variation in the LCOE cost components. Since there is still limited research on floating solar PV in Indonesia, a review of the support schemes in other countries also provided another insight into how to increase the economic potential of FSPV in Indonesia.

8.1.3 Results Finding Discussion

The results and findings from Chapters 4 to 7 provided answers to each research sub-questions by using a specific methodology for each question. The results presented the outcomes of the data analysis process and mapping of FSPV in Indonesia, including the selected site, technical potential, economic potential, and recommended support schemes to increase the economic potential. This discussion will provide insights into the significance of the findings to the research sub-questions.

First, the literature review on each site selection criterion as well as documentation in the current market situation of FSPV, revealed that not all of the criteria used in the other literature are relevant for technical potential and, in some cases, only applicable to economic potential. The selection criterion mentioned in other literature is quite generalized and mostly does not define the reasoning behind the selected parameter and range value. Therefore, reviewing each possible criterion and creating the own selection criteria in this study provides the rationale for the site selection of FSPV. After selecting the criteria, the relevant dataset to the criteria is used as an input for QGIS, thus able to provide the location of suitable water bodies and their total available area.

The use of three different methods to measure the annual electricity generation from FSPV helps to answer the technical potential of FSPV in Indonesia while providing insights on the possibility of having a higher energy generation in floating solar compared to the ground mounted. As the water bodies already identified in the site suitability assessment chapter, the use of QGIS further eased the author to obtain the technical potential of FSPV in Indonesia through different methods. The result also shows similar technical potential results in the Cirata reservoir in Indonesia from the other study.

As ceiling electricity prices are applicable in Indonesia, obtaining the LCOE of FSPV in each water body and later compared to the ceiling prices helps to gain insights into the economic potential of FSPV in Indonesia. The results also revealed that the economic potential coverage level of FSPV in Indonesia cannot be generalized due to the differences in ceiling prices, demographic, as well as solar irradiance between different provinces. These affect the LCOE calculations and, subsequently the economic potential.

Moreover, the investigation of potential also broadens to a larger context: the electricity demand coverage. The finding shows that the demographic situation in Indonesia has a significant factor in the difference in potential coverage between provinces in the country. If all technical potential of FSPV is installed in Indonesia with 5% coverage, the FSPV is still able more than 25% of current electricity demand in most of the provinces. However, this coverage is significantly drop in the economic potential. In addition, if there are no changes of electricity distribution as well as with a generalized growth electricity demand in 2030, the only location that still holds relative high coverage is mainly observed in the eastern part of Indonesia. Table 8-1 summarizes the results of technical and economic potential.

Table 8-1 Summary of Technical and Economic Potential at 5% Water Occupancy

No.	Province	Technical Potential				Economic Potential			
		Installed Capacity [MWp]	Annual Generation [GWh]	Current Coverage [%]	2030 Coverage [%]	Installed Capacity [MWp]	Annual Generation [GWh]	Current Coverage [%]	2030 Coverage [%]
1	Aceh	394	520	16	10.5	52	71	2.2	1.3
2	Bali	154	198	4	2.4	9	14	0.35	0.2
3	Banten	68	88	0.4	0.2	34	45	0.24	0.1
4	Bengkulu	51	70	6	4.1	39	56	6.2	3.1
5	DI Yogyakarta	11	15	0.4	0.3	2	3	0.1	0.06
6	DKI Jakarta	39	53	0.2	0.1	30	42	0.12	0.1
7	Gorontalo	121	178	26	17.6	10	15	2.4	1.3
8	Jambi	367	466	25	13.8	28	35	1.7	1.0
9	Jawa Barat	1,419	1,970	3.5	2.4	92	127	0.3	0.2
10	Jawa Tengah	1,045	1,516	5.3	3.6	66	96	0.56	0.3
11	Jawa Timur	315	450	1	0.7	93	139	0.52	0.2
12	Kalimantan Barat	1,007	1,220	61	26.7	72	96	7.1	3.0
13	Kalimantan Selatan	398	510	15	10.3	25	32	1	0.6
14	Kalimantan Tengah	789	1,010	60	40.2	35	46	5.7	2.5
15	Kalimantan Timur	2,101	2,736	58	39.5	66	83	2.3	1.2
16	Kalimantan Utara	6	7	3	1.6	3	4	1.7	0.9
17	Kepulauan Bangka Belitung	94	110	9	5.4	33	42	6.1	2.7
18	Kepulauan Riau	273	330	33	22.1	92	116	13.1	7.4
19	Lampung	865	1,100	20	13.2	17	23	0.7	0.3
20	Maluku	142	180	29	19.5	46	62	14	7.2
21	Maluku Utara	153	200	31	20.1	48	65	21	8.7
22	Nusa Tenggara Barat	324	470	20	13.0	186	287	15	7.3
23	Nusa Tenggara Timur	215	340	27	17.8	48	77	6.5	3.4
24	Papua	3,662	4,941	387	259.3	3,511	4,753	384	219.9
25	Papua Barat	1,358	1,710	276	185.8	1,187	1,516	255	148.9
26	Riau	1,063	1,360	24	16.3	18	23	0.5	0.3
27	Sulawesi Barat	0.5	1	0.2	0.1	0.4	0.56	0.13	0.1
28	Sulawesi Selatan	5,221	8,049	109	80.1	100	146	2.9	1.4
29	Sulawesi Tengah	2,306	3,381	234	158.1	50	73	5.3	2.9
30	Sulawesi Tenggara	96	130	11	7.3	53	76	7.5	3.9
31	Sulawesi Utara	301	402	19	12.8	23	34	1.7	0.9
32	Sumatera Barat	1,806	2,294	59	39.8	10	13	0.5	0.3
33	Sumatera Selatan	813	1,040	17	11.6	20	26	0.9	0.4
34	Sumatera Utara	6,162	8,049	63	42.8	48	64	0.6	0.3

The sensitivity analysis is used to identify which parameters are sensitive to the economic potential, hence becoming the foundation for proposing recommended support schemes but also checks whether the results of economic potential can be consistent if there are changes in the parameters. It is found that capital expenditures are the most sensitive parameter, as shown in the changes of economic potential by changing the cost of capital by ±10% and estimated cost reduction in 2030. The change in capital expenditure leads to an increase of economic potential by 44% if the capital cost is reduced by 10% and a decrease of 48% if the capital cost is increased by 10%. Since the reference of capital cost, as shown in Table 3-8, has a variation of more than 10% in each component, it would seem that the economic potential result in this study might not be applicable. However, this can be argued that the selected base value for each component capital cost is carefully selected. For example, the cost of a solar PV module is already based on the published price in the commercial market in Indonesia. The cost of balance of system, construction, permit, and environmental study is based on the Indonesian case literature. In addition, the floating system cost is based on the detailed project report by CECP in 2022 for actual implementation.

Finally, the support schemes analysis was performed to focus not only on Indonesia but also on other countries to have other perspectives where the conditions for floating solar deployment could be different. The competing technology, coal, is also reviewed to gain more context on the electricity supply landscape in Indonesia. With the combination of the current implemented regulations and schemes in Indonesia, findings on the support schemes of other countries, as well as the sensitivity analysis, the recommended support schemes to increase the economic potential are identified with certain priorities on the water occupancy level, capital costs incentive, and feed-in tariff or ceiling prices review.

8.1.4 Discussion on Water Evaporation and Savings

Floating solar PV's main advantage compared to ground-mounted solar PV is its benefit of reducing water evaporation. This benefit will be meaningful for the region with a water scarcity issue. Floating solar affects water evaporation, as studied by Pouran et al. (2022a), and can effectively reduce evaporation, particularly in areas that experience high levels of sunlight and high rates of evaporation. As the solar panels are mounted on floating platforms on top of the water, they create a shading effect, reducing the amount of direct sunlight that reaches the water's surface. This will reduce the rate of water evaporation, resulting in less water loss from the reservoirs or lakes where the FSPV is installed.

Pouran et al. (2022b) model calculate the reduced evaporation based on water occupancy. For example, with 5% water occupancy, it is estimated that the reduced evaporation will be 3.4%. The reduced water evaporation percentage is then used for calculating the volume of water evaporation. The volume of water evaporation is calculated based on the water evaporation data in Indonesia from Putra et al. (2021) from Indonesian Agency for Meteorological Climatological and Geophysics. The volumetric amount of water reduction is obtained using the combination of this information and the total water surface area for each water body. Figure 8-1 shows the result of water evaporation reduction in Indonesia based on the economic potential with different water occupancy.

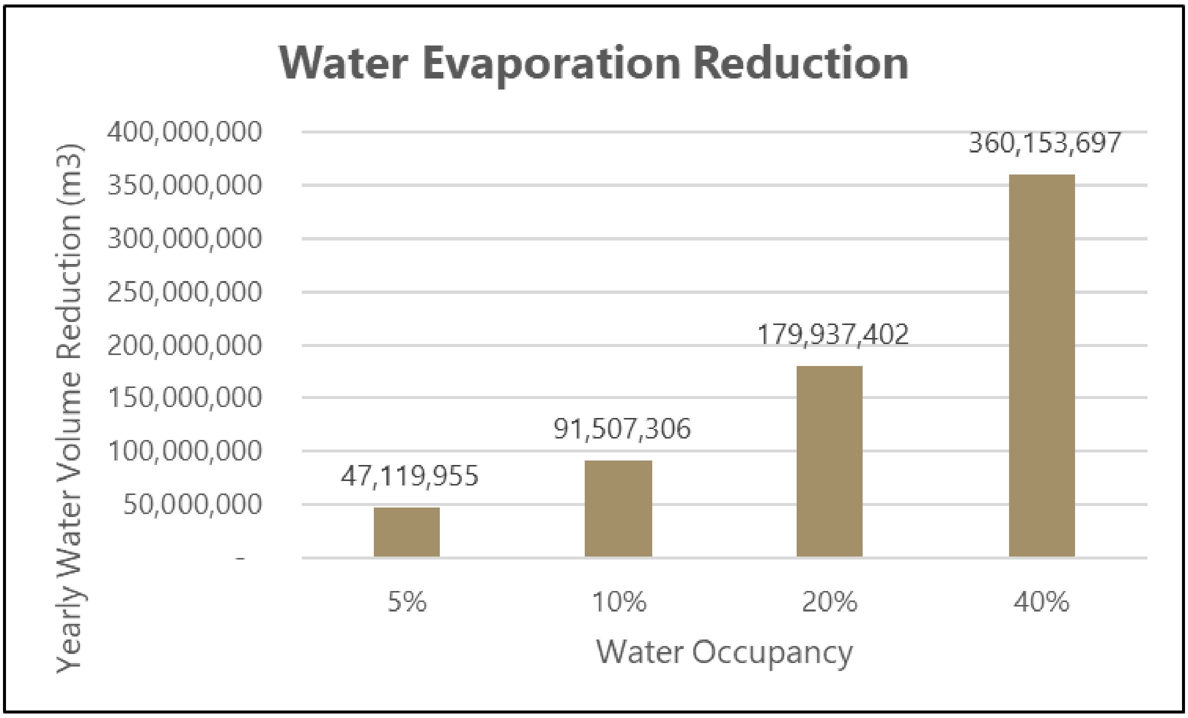

Figure 8-1 Water Evaporation Reduction

As expected, increasing the water occupancy of FSPV in water bodies will increase the water evaporation reduction. This water evaporation can be translated into water saving. Thus, it can be further processed and distributed for broader purposes. For example, water saving can increase the electricity generation from hydropower plants if the FSPV is coupled with the hydropower plant. Another possibility is to use the water for supplying another type of energy carrier, such as green hydrogen, while using the FSPV as the source of electricity. However, for this research, the impact of water saving will be illustrated by comparing it with the water consumption in Indonesia based on Central Agency on Statistics (BPS-Statistics Indonesia, 2022).

The yearly water consumption in Indonesia from BPS-Statistics Indonesia (2022) is about 4.35 billion m^3. If the water occupancy of FSPV is 5%, the water saving from evaporation reduction can supply 1.1% of water consumption for Indonesia. This can be otherwise translated that the accumulated yearly water savings could be enough to supply around 3 million people in Indonesia. However, as the installed capacity of FSPV could be different for every province and its water consumption, different water consumption coverage is expected. Figure 8-2 shows the spatial profile for the percentage coverage of water consumption for every province in Indonesia at 5% water occupancy of FSPV.

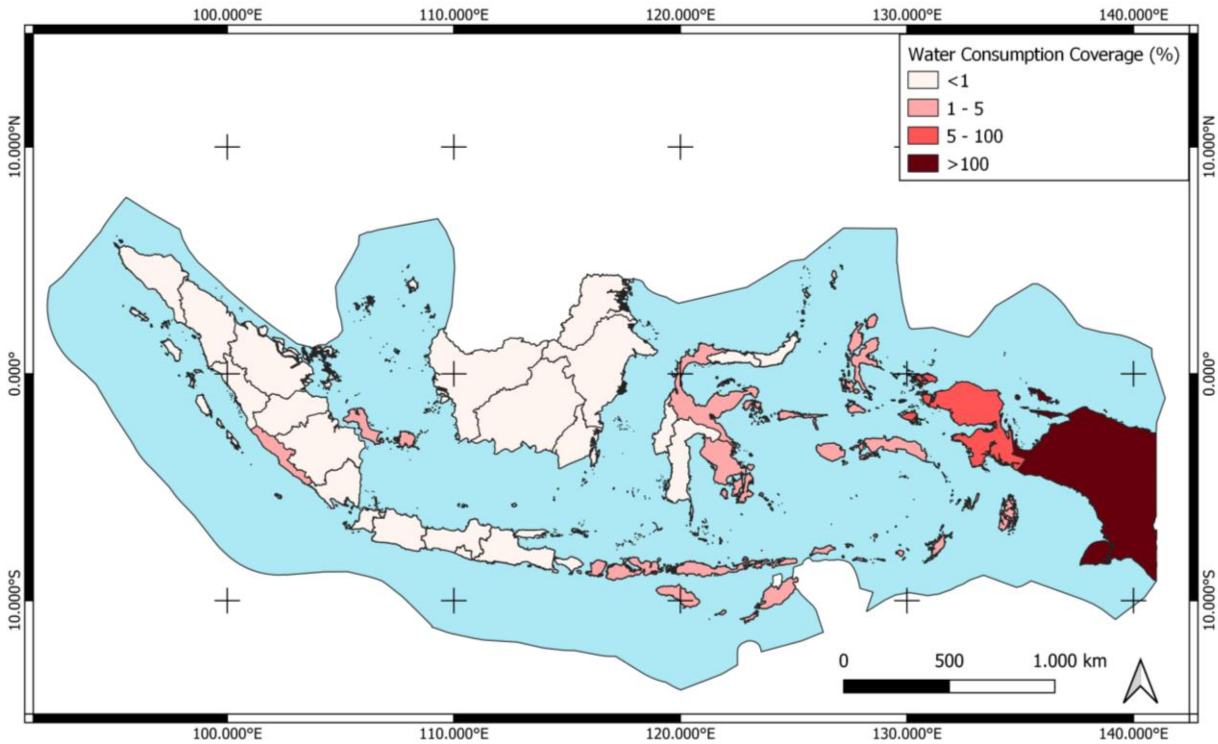

Figure 8-2 Water Consumption Coverage – 5% Water Occupancy

Based on Figure 8-2, less than 1% of water consumption coverage is seen in most provinces. There are only nine provinces with more than 1% coverage, with Papua being the only province that can supply more than the water consumed. This is also, in fact, due to the difference in total population in Indonesia, where most people live in the western part of Indonesia. Details of the water consumption coverage of every province are shown in Appendix C.

As the data on water consumption from BPS-Statistics Indonesia (2022) refers to the distributed water from the water distribution company in Indonesia, thus the financial value of the water savings also can be estimated. Based on the water cost of IDR 1,900/m^3 or around 0.12 USD/m^3 for the lowest household category from one of the water companies in Indonesia (PDAM, 2023), the yearly financial value of water savings is US$6 million for 5% water occupancy and can be up to US$45 million for 40% water occupancy.

8.2 Limitations of the Study

This section will discuss the limitations of the thesis even though the study provided valuable insights on site suitability criteria, technical potential, and economic potential. There are several limitations to the study that are identified and their implications for the research outcomes thus need to be acknowledged.

8.2.1 Limitations on Spatial Resolution

The spatial resolution of this study has 250m x 250m for calculating the wind speed, ambient temperature, and solar irradiance from ERA5, Global Solar Atlas, and Global Wind Atlas. Meanwhile, a 2km x 2km resolution from NREL is used to calculate the technical potential with the Time Series Method, although it is bias corrected through the spatial resolution from ERA5 and Global Solar Atlas with the resolution of 250m x 250m. While the data sources used in this study are from a reliable organization, such spatial resolution could affect the accuracy of the technical and economic potential results. The potential error from the spatial resolution may result in a higher or lower technical and economic potential. However, even though there could be differences in the calculation due to the spatial resolution, the cause of the total results is expected to be minor. For example, Global Solar Atlas had a validation report in 2019 on its dataset by comparing the dataset they provided with the field measurements in Indonesia (ESMAP, 2019). The difference between the dataset to the ground measurement in Indonesia is 0.6% in Bukit Kototabang, Sumatra, and -4.6% in Palangkaraya, Kalimantan.

8.2.2 Limitations on Technical Potential Calculation

Using the Zonal Statistics tool in QGIS may affect each water body's actual technical potential calculation. This is because the Zonal Statistics retrieved the average value of wind speed, ambient temperature, and solar irradiance in a specific water body then the value is used to calculate electricity generation. Meanwhile, in reality, each solar PV panel will experience a different wind speed, ambient temperature, and solar irradiance, thus will provide a difference in the electricity generation.

8.2.3 Limitations on Water Bodies Dataset

Since the secondary data used to build up the water bodies' location in Indonesia is from OpenStreetMap, there is a potential error in the location of water bodies and their total area. Volunteers and local knowledge provide OpenStreetMap data; thus, quality control of the data is the downside of OpenStreetMap. This is true considering that the author discovered a redundancy of water bodies in the dataset. Therefore, the author tried to minimize this downside by checking each water body by comparing between water body's total area and coordinates identified in the OpenStreetMap. If there are two water body data with similar coordinates, vector shape, and total area, then one water body is omitted from the dataset. The water bodies that are used in this study are already filtered and quality checked in terms of double entries, although there is still a potential error that remains coming from other aspects, namely location accuracy and total area accuracy. However, even though there could be differences in the calculation due to the potential errors from location and total area accuracy, the difference is expected to be minor. This refers to the evaluation activities and reports on the OpenStreetMap quality in Indonesia performed by universities in Indonesia and OpenStreetMap in 2012 (UGM & OpenStreetMap, 2012). The report investigated two datasets: buildings and roads. The report concluded that the spatial accuracy of OpenStreetMap data in Indonesia is considered adequate based on the comparison with the reference data and field verification.

8.2.4 Limitations on Cost Model and Assumption

One of the limitations of this study is the assumption made regarding the cost components of FSPV and the cost model used in the study. While the cost references used in this thesis were obtained from reputable sources and carefully selected, the actual costs of FSPV may vary significantly depending on the site locations. For example, the cost per Wp of FSPV in Papua may differ from that of FSPV in Java. In addition, the cost model per Wp used for calculating the capital expenditures is assumed to be linear regardless of the system size, while it may be different with different installed capacities. Thus, there will be an impact on the economic potential calculation. As discussed previously, the choosing of cost, especially the capital costs has a significant impact on the result of the economic potential, as shown in the sensitivity results.

8.2.5 Limitations on Social Aspect

While this study is focused on the technical and economic potential of FSPV in Indonesia with some extent to environmental factors coming from the water occupancy criterion, it still needs to fully account for the social acceptance of FSPV in the communities surrounding the water bodies. The surrounding communities are usually consulted if a project is developed in their location, which may lead to community resistance. This community resistance can arise due to several factors, such as perceived impacts on the water bodies, natural habitats, and economic impact if fishing and recreational activities exist.

9 Recommendations

This chapter will present the recommendations for future research based on the result of this study to enrich the insights already provided in this study. The recommendations proposed in this chapter are derived from the identified research gaps, limitations, and findings of this study. The recommendations are comprised of technical, economic, environmental, and social items. By addressing these recommendations, future studies could contribute to a more comprehensive understanding of the FSPV potential in general as well as in Indonesia.

9.1 Hybrid Integration of FSPV

As identified in Chapter 6, if all economic potential of FSPV in Papua and Papua Barat is implemented, there will be a surplus of electricity and water savings. This additional electricity and water can be another power source for another form of the renewable energy system, such as green hydrogen. It also can be additional resources to increase electricity generation from hydropower if the FSPV is installed in the reservoir of hydropower through the decrease of water evaporation. As Indonesia has a considerable installed capacity of hydropower, a study-specific to the hybrid integration of FSPV with hydropower that focuses on the electricity generation output and cost-effectiveness can be considered for future research. For example, a study focused on the impact of fluctuations of FSPV hybrid with hydropower generation due to seasonal changes in Indonesia could understand the optimal combination of FSPV and hydropower. Another aspect that can be studied is about the cost-benefit of using the existing transmission lines for FSPV and the possibility of hydropower becoming a seasonal storage.

9.2 FSPV Electricity Generation

This study shows the potential impact of module efficiency on the performance of floating solar on a limited occasion by comparing the method for the technical potential. The cooling effect of water on solar modules has been identified as a potential advantage of floating solar, and future research could be done on more detailed analyses of this effect. This will subsequently impact the FSPV electricity generation and the technical potential.

9.3 Water Occupancy and Environmental Impact

The impact of FSPV on the water body and its occupancy is an important aspect that needs to be studied in more detail. This is because the change in water occupancy significantly impacts the potential deployment of FSPV. For example, an assessment of the long-term implications of FSPV deployment on water quality, biodiversity, and ecosystems can be considered for future research to determine the safe limit of water occupancy by considering the environment. The literature review in this study shows a certain range of optimal water occupancy percentages for FSPV. However, this investigation could be more detailed by considering the water bodies' location, purposes of water bodies such as for irrigation, and the environmental conditions.

9.4 Cost Data and Model

While this thesis has provided a cost analysis in the economic potential context of FSPV in Indonesia, future studies could gather more comprehensive data and explore opportunities for data sharing and collaboration across different stakeholders in Indonesia. In addition, as this thesis used a linear cost model for FSPV, an investigation on the potential cost model that fits the economic scale could be considered to increase the accuracy of the economic potential of FSPV in Indonesia.

9.5 Social Acceptability

This research has already explored the technical and economic potential of FSPV in Indonesia. However, the social aspects of this technology could play a crucial role in its potential deployment in the country. An engagement of local communities and stakeholders can be considered to understand their perceptions towards FSPV, especially in the water bodies where it is used for economic activity such as fisheries and recreation activities.

10 Conclusions

This chapter will present the conclusions of this thesis by answering the research sub-questions and main question. First, the research sub-questions answers will be presented in section 10.1. It is then followed by answering the main research question in section 10.2.

10.1 Research Sub Questions

The research sub-questions are addressed in this section based on the findings from Chapters 4 to 7. The research sub-questions are used to answer specific parts of the main research question and thus will contribute to answering the main question.

10.1.1 Sub Question 1 Answer

SQ1: *"What is the total available and suitable area to install floating solar PV in Indonesia?"*

The total available area is obtained from data on water bodies in OpenStreetMap. Quality control is performed to minimize the downside of OpenStreetMap in data quality, and a total area of 6,299 km^2 is identified based on 16,565 freshwater bodies spread throughout Indonesia. Meanwhile, marine water areas of Indonesia are more than 6 million km^2.

Identifying suitable water bodies and their total area requires a different approach by creating a site selection criterion to filter the unsuitable locations. The site selection criteria are created based on a literature review and analysis of each possible criterion. Water conditions in freshwater, maximum water occupancy, historical maximum wind speed, and protected lake are the criteria for selecting suitable water bodies. It is to be noted that protected lakes will be studied for this thesis since Indonesian regulations allow an energy infrastructure to be installed in their protected lakes.

Based on the filtered criteria, 16,306 water bodies are suitable for FSPV installation, with a total area of water bodies up to 3,652 km^2. If protected lakes are included, the total water bodies become 16,322 with an area of up to 6,274 km^2. Since there is a maximum water occupancy criterion, the total area is limited between 5% to 40%; thus, the suitable area is 176.4 km^2 for 5% occupancy and 1,410.8 km^2 for 40% water occupancy. If protected lakes are included, the total suitable area becomes 307.5 km2 for 5% water occupancy up to 2,459.8 km^2 at 40% water occupancy.

10.1.2 Sub Question 2 Answer

SQ2: *"What is the technical potential of floating solar PV in Indonesia?"*

The technical potential is calculated in Chapter 5 and uses the suitable water bodies from Chapter 4, as answered in SQ1. There are two terms to measure the technical potential of FSPV in Indonesia, namely the installed capacity potential and annual electricity generation potential. The installed capacity potential is measured by calculating the effective area of the FSPV. Meanwhile, area occupancy is the total area of a certain FSPV in a water body including the other components in a floating solar system such as cabling, floats, and inverter. Thus, the area occupancy is larger than the effective area. As for the annual electricity potential, three different methods are used to calculate electricity generation. The method for measuring the electricity generation is then compared to obtain insights about floating solar. The result shows that Simple Method in the study shows the highest result in electricity generation due to its calculation only depending on the standard test conditions. Meanwhile, the Time Series method shows the lowest possible electricity generation due to the potential of not implementing the impact of cooling from water. Therefore, the FSPV Modified method is used to present the annual electricity generation potential since it is based on FSPV mathematical model and covers all suitable water bodies in Indonesia.

The installed capacity potential that is identified in this study is 33,409 MWp at 5% water occupancy and gradually increased by increasing the water occupancy up to 267,300 MWp at 40% water occupancy. Meanwhile, the annual electricity generation potential of FSPV in Indonesia that is calculated by using the FSPV Modified method is 38,690 GWh at 5% water occupancy up to 324,110 GWh at 40% water occupancy.

10.1.3 Sub Question 3 Answer

SQ3: *"What is the current economic potential of floating solar PV in Indonesia?"*

The economic potential is calculated by measuring the LCOE of FSPV in each suitable water body and comparing it with the applicable ceiling prices in Indonesia. The term "current" is used in the SQ3 due to the potential of technological advancement in floating solar, considering that it is still nascent. The economic potential is also presented by measuring the installed capacity potential and annual electricity generation potential. In addition, the potential of FSPV is also being analyzed in a broader context by comparing it with the demand for electricity per province.

There is a significant drop in installed capacity potential and annual electricity generation from technical to economic potential ranging from 81 to 89%. The economic installed capacity potential that is identified in Indonesia is 6,401 MWp with annual electricity generation of 8,854 GWh at 5% water occupancy. These figures are gradually increased by increasing the water occupancy with the installed capacity potential and electricity generation of 45,777 MWp and 63,267 GWh at 40% water occupancy. It is also identified that the lowest percentage drop of potential and highest demand coverage is in the Eastern part of Indonesia, while the highest percentage drop of potential and lowest energy demand coverage is in Java. This is mainly because of the combination between the demographic situation in the country, water bodies availability, and the applicable ceiling prices within the region. The eastern part of Indonesia has higher ceiling prices with much lower population in comparison to the western part of Indonesia, where the population is quite dense as well as with lower ceiling prices.

10.1.4 Sub Question 4 Answer

SQ4: *"What are the current support schemes and regulations, and what support schemes can be recommended to increase the economic potential of floating solar PV in Indonesia?"*

This study identifies four key current schemes and regulations: the water occupancy regulation, national target plan, ceiling prices, and minimum local content requirements. The current regulation in Indonesia requires the FSPV deployment with a maximum of 5% water occupancy in a water body. There are also already seven water bodies planned for the FSPV installation of up to 612 MWp. As for the ceiling prices, the value is used as an indicator to determine the economic potential of FSPV in Indonesia. Meanwhile, there are also minimum local content requirements that need to be fulfilled for solar PV projects in Indonesia, regardless of the type of installation.

The recommended support schemes for FSPV are built based on the sensitivity analysis and study about FSPV implementation in other countries. The sensitivity shows that capital expenditures significantly increase economic potential, followed by choosing a lower discount rate and operational expenditures. Meanwhile, an increase in ceiling prices also increases the economic potential, with the amount of potential increase being higher than changing the discount rate and operational expenditures.

A study of the FSPV implementation in other countries shows that a variety of support schemes can be considered, such as support in research and development, creating a national consortium, and targeting a minimum solar PV installation with a penalty. Fiscal support is a scheme widely used in other countries through feed-in tariffs or capital cost incentives. This study summarized a list of possible support schemes that could be implemented in Indonesia namely capital expenditure fiscal incentive, feed-in tariff, re-evaluate the ceiling prices, utilization of carbon tax, workforce development, target FSPV installation with penalty, national consortium, soft loan financing, and changes in water occupancy. However, the stakeholders only need to consider three sets of the most important schemes to increase the economic potential, namely increasing the maximum water occupancy, capital cost incentive, and changes in ceiling prices. By increasing the water occupancy to 10%, the increased economic potential is 6 GWp which is a similar size to the economic potential at 5% water occupancy. The capital cost support could increase the economic potential by 2.8 GWp. Meanwhile, altering the first ten years of ceiling prices into a 10% higher current price could increase economic potential up to 0.8 GWp. This study proposes that the combination of increasing the water occupancy together with the capital costs incentive is the preferable solution to increase the economic potential of FSPV in Indonesia. Together with investment of large-scale solar production facility, around 20.5 GWp of installed capacity of FSPV is expected by the end of 2030.

10.2 Main Question

"What is the technical and current economic potential of floating solar PV in Indonesia, and what schemes required to increase its economic potential?"

The answers from each sub-question form the response to the main research question of this study. In conclusion, floating solar PV could be another renewable energy resource to support the energy transition of Indonesia with the technical potential of an installed capacity of 33,409 MWp and an annual electricity generation potential of 38,690 GWh at 5% water occupancy. This could be even higher if the cap of maximum water occupancy in the country's regulation is increased. The technical potential of FSPV in Indonesia could reach up to 267,300 MWp with an annual electricity generation of 324,110 GWh at 40% water occupancy. Based on the potential at 40% water occupancy, the FSPV is able to cover the current electricity demand in Indonesia, albeit the degree of coverage is different between the provinces.

However, the economic potential of floating solar PV in this study is significantly less than its technical potential, with only 6,401 MWp installed capacity potential and 8,854 GWh of annual electricity generation at 5% water occupancy. Meanwhile, the economic potential of FSPV at 40% water occupancy is 45,777 MWp and 63,267 GWh. This is mainly due to the implemented maximum electricity tariff that is capped based on the installation location and total installed capacity. The maximum tariff becomes the ceiling price of the electricity cost. If the LCOE result of the FSPV is higher than the ceiling tariff, then it is not considered economic potential.

The trend of the economic potential of FSPV in Indonesia can be easily distinguished between the Eastern and Western parts of the country. This study shows that the economic potential is higher in the eastern provinces of Indonesia, such as Papua, compared to the western provinces, such as Java Island. This is because of higher location factors and ceiling prices for the provinces in the eastern part of the country, thus leading to a higher economic potential in the region. However, this trend is not noticeable in the technical potential map. The provinces in Sumatra and Java Island still hold comparable technical potential in comparison to the other provinces in the eastern part.

Based on the technical potential result and the demand requirements in the country, Indonesia holds a moderate amount of potential to meet the electricity demand at 5% water occupancy with around 17% of current national demand coverage. Meanwhile, at 40% water occupancy, the FSPV is able to meet the whole current electricity demand in the country. However, due to the significant drop of potential from the technical potential to the economic potential, FSPV with 5% water occupancy is only able to cover

3% of the current national demand and up to 23% at 40% water occupancy mainly because of the challenges in the requirements to meet the ceiling prices and the cost of the FSPV itself.

Nevertheless, there is still incentive to have FSPV especially in the eastern part of the country where it is capable to meet a large portion of the electricity demand. In addition, the possible of cost reduction in the future will create more opportunities for FSPV to compete with the other technologies and meet the ceiling prices requirement. However, support schemes from the government is still required to increase the economic potential of FSPV in Indonesia especially for the western part of the country in order the FSPV become a large share of renewable energy in the country's energy transition plan.

There are nine identified support schemes through different mechanisms, from providing a financial incentive, support on research and development, and creating an organization for sharing knowledge between stakeholders to increase the economic potential of FSPV in Indonesia. However, three support schemes could be considered in this study. First, increasing the maximum water occupancy of 5% into a higher figure. Second, provide capital expenditure subsidies for the FSPV project. Finally, a review of the applicable ceiling prices with potential revision on the first ten years' ceiling price and the applicable tariff for a larger installed capacity category. The recommended combination of schemes is by regulating the water occupancy to a higher figure as well as capital expenditure incentives. In addition, Indonesia needs to arrange a relax requirement in the local content while constructing a 3 GW solar production factory. Together with the implementation of support schemes and planning of domestic solar production facility, the country target of 20 GWp installed capacity of solar PV in 2030 can be achieved by floating solar.

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Appendix A – Technical Potential per Provinces

Table A-1 Technical Potential Installed Capacity and Annual Electricity Generation from 5% to 40% Water Occupancy

No	Province	Total Water Bodies	Installed Capacity [MWp]	Simple [GWh]	FSPV Modified [GWh]
1	Aceh	703	394 – 3,150	530 – 4,420	520 – 4,360
2	Bali	211	154 – 1,233	203 – 1,700	198 – 1,650
3	Banten	472	68 – 543	91 – 770	88 – 740
4	Bengkulu	185	51 – 405	73 – 610	70 – 590
5	DI Yogyakarta	223	11 – 88	16 – 130	15 – 120
6	DKI Jakarta	387	39 – 315	55 – 460	53 – 440
7	Gorontalo	25	121 – 967	200 – 1,540	178 – 1,490
8	Jambi	295	367 – 2,934	501 – 3,960	466 – 3,900
9	Jawa Barat	4,349	1,419 – 11,359	2,030 – 16,980	1,970 – 16,550
10	Jawa Tengah	498	1,045 – 8,361	1,559 – 13,070	1,516 – 12,690
11	Jawa Timur	652	315 – 2,517	470 – 3,950	450 – 3,820
12	Kalimantan Barat	483	1,007 – 11,758	1,340 – 16,810	1,220 – 15,640
13	Kalimantan Selatan	322	398 – 3,188	530 – 4,430	510 – 4,300
14	Kalimantan Tengah	194	789 – 6,315	1,060 – 8,830	1,010 – 8,540
15	Kalimantan Timur	492	2,101 – 16,812	2,869 – 23,710	2,736 – 22,910
16	Kalimantan Utara	35	6 – 49	8 – 70	7 – 67
17	Kepulauan Bangka Belitung	230	94 – 752	120 – 1,040	110 – 1,000
18	Kepulauan Riau	572	273 – 2,183	350 – 2,960	330 – 2,790
19	Lampung	147	865 – 6,918	1,130 – 9,480	1,100 – 9,260
20	Maluku	164	142 – 1,134	190 – 1,570	180 – 1,530
21	Maluku Utara	69	153 – 1,224	210 – 1,770	200 – 1,720
22	Nusa Tenggara Barat	533	324 – 2,596	490 – 4,130	470 – 4,010
23	Nusa Tenggara Timur	675	215 – 1,720	360 – 3,010	340 – 2,880
24	Papua	880	3,662 – 29,294	5,045 – 42,310	4,941 – 41,380
25	Papua Barat	245	1,358 – 10,868	1,750 – 14,680	1,710 – 14,380
26	Riau	219	1,063 – 8,501	1,410 – 11,790	1,360 – 11,410
27	Sulawesi Barat	18	0.5 – 5	1 – 7	1 – 6
28	Sulawesi Selatan	897	5,221 – 41,773	8,265 – 63,690	8,049 – 62,010

No	Province	Total Water Bodies	Installed Capacity [MWp]	Simple [GWh]	FSPV Modified [GWh]
29	Sulawesi Tengah	169	2,306 – 18,453	3,472 – 28,730	3,381 – 28,310
30	Sulawesi Tenggara	245	96 – 771	140 – 1,160	130 – 1,120
31	Sulawesi Utara	148	301 – 2,404	469 – 3,460	402 – 3,370
32	Sumatera Barat	114	1,806 – 14,453	2,347 – 19,650	2,294 – 19,210
33	Sumatera Selatan	371	813 – 6,504	1,070 – 8,960	1,040 – 8,740
34	Sumatera Utara	1,336	6,162 – 49,298	8,522 – 68,400	8,049 – 67,400

Appendix B – Economic Potential per Provinces

Table B-1 Economic Potential Installed Capacity and Annual Electricity Generation from 5% to 40% Water Occupancy

No	Province	Installed Capacity [MWp]	Annual Generation [GWh]
1	Aceh	52 – 224	71 – 321
2	Bali	9 – 31	14 – 51
3	Banten	34 – 206	45 – 281
4	Bengkulu	39 – 161	56 – 240
5	DI Yogyakarta	2 – 27	3 – 40
6	DKI Jakarta	30 – 133	42 – 186
7	Gorontalo	10 – 37	15 – 58
8	Jambi	28 – 106	35 – 139
9	Jawa Barat	92 – 928	127 – 1.374
10	Jawa Tengah	66 – 247	96 – 380
11	Jawa Timur	93 – 336	139 – 527
12	Kalimantan Barat	72 – 198	96 – 273
13	Kalimantan Selatan	25 – 149	32 – 200
14	Kalimantan Tengah	35 – 148	46 – 205
15	Kalimantan Timur	66 – 240	83 – 314
16	Kalimantan Utara	3 – 39	4 – 53
17	Kepulauan Bangka Belitung	33 – 121	42 - 162
18	Kepulauan Riau	92 – 469	116 – 620
19	Lampung	17 – 109	23 – 150
20	Maluku	46 – 214	62 – 318
21	Maluku Utara	48 – 556	65 – 827
22	Nusa Tenggara Barat	186 – 1,786	287 – 2,884
23	Nusa Tenggara Timur	48 – 449	77 – 754
24	Papua	3,511 – 29,049	4,753 - 41,092
25	Papua Barat	1,187 – 9,600	1,516 – 12,833
26	Riau	18 – 65	23 – 87
27	Sulawesi Barat	0.4 – 5	0.56 – 6
28	Sulawesi Selatan	100 – 464	146 – 719

No	Province	Installed Capacity [MWp]	Annual Generation [GWh]
29	Sulawesi Tengah	50 – 240	73 – 362
30	Sulawesi Tenggara	53 – 282	76 – 416
31	Sulawesi Utara	23 – 111	34 – 167
32	Sumatera Barat	10 – 57	13 -79
33	Sumatera Selatan	20 – 94	26 – 129
34	Sumatera Utara	48 - 277	64 – 383

Appendix C – Electricity and Water Coverage

Table C-1 Electricity Demand Coverage Potential – Technical Potential - 5% Water Occupancy

No	Province	Yearly Demand [GWh]	Current Potential Coverage [%]	2030 Potential Coverage [%]
1	Aceh	3,339	16	10.5
2	Bali	5,622	4	2.4
3	Banten	25,305	0.4	0.2
4	Bengkulu	1,152	6	4.1
5	DI Yogyakarta	3,424	0.4	0.3
6	DKI Jakarta	36,533	0.2	0.1
7	Gorontalo	684	26	17.6
8	Jambi	2,284	25	13.8
9	Jawa Barat	56,298	3.5	2.4
10	Jawa Tengah	28,513	5.3	3.6
11	Jawa Timur	42,743	1	0.7
12	Kalimantan Barat	3,085	61	26.7
13	Kalimantan Selatan	3,340	15	10.3
14	Kalimantan Tengah	1,697	60	40.2
15	Kalimantan Timur	4,685	58	39.5
16	Kalimantan Utara	297	3	1.6
17	Kepulauan Bangka Belitung	1,384	9	5.4
18	Kepulauan Riau	1,009	33	22.1
19	Lampung	5,635	20	13.2
20	Maluku	623	29	19.5
21	Maluku Utara	672	31	20.1
22	Nusa Tenggara Barat	2,442	20	13.0
23	Nusa Tenggara Timur	1,288	27	17.8
24	Papua	1,288	387	259.3
25	Papua Barat	622	276	185.8
26	Riau	5,644	24	16.3
27	Sulawesi Barat	482	0.2	0.1
28	Sulawesi Selatan	6,792	109	80.1
29	Sulawesi Tengah	1,444	234	158.1

No	Province	Yearly Demand [GWh]	Current Potential Coverage [%]	2030 Potential Coverage [%]
30	Sulawesi Tenggara	1,208	11	7.3
31	Sulawesi Utara	2,116	19	12.8
32	Sumatera Barat	3,897	59	39.8
33	Sumatera Selatan	6,038	17	11.6
34	Sumatera Utara	12,719	63	42.8

Table C-2 Electricity Demand Coverage Potential – Economic Potential - 5% Water Occupancy

No	Province	Yearly Demand [GWh]	Current Potential Coverage [%]	2030 Potential Coverage [%]
1	Aceh	3,339	2.2	1.3
2	Bali	5,622	0.35	0.2
3	Banten	25,305	0.24	0.1
4	Bengkulu	1,152	6.2	3.1
5	DI Yogyakarta	3,424	0.1	0.06
6	DKI Jakarta	36,533	0.12	0.1
7	Gorontalo	684	2.4	1.3
8	Jambi	2,284	1.7	1.0
9	Jawa Barat	56,298	0.3	0.2
10	Jawa Tengah	28,513	0.56	0.3
11	Jawa Timur	42,743	0.52	0.2
12	Kalimantan Barat	3,085	7.1	3.0
13	Kalimantan Selatan	3,340	1	0.6
14	Kalimantan Tengah	1,697	5.7	2.5
15	Kalimantan Timur	4,685	2.3	1.2
16	Kalimantan Utara	297	1.7	0.9
17	Kepulauan Bangka Belitung	1,384	6.1	2.7
18	Kepulauan Riau	1,009	13.1	7.4
19	Lampung	5,635	0.7	0.3
20	Maluku	623	14	7.2
21	Maluku Utara	672	21	8.7
22	Nusa Tenggara Barat	2,442	15	7.3
23	Nusa Tenggara Timur	1,288	6.5	3.4

No	Province	Yearly Demand [GWh]	Current Potential Coverage [%]	2030 Potential Coverage [%]
24	Papua	1,288	384	219.9
25	Papua Barat	622	255	148.9
26	Riau	5,644	0.5	0.3
27	Sulawesi Barat	482	0.13	0.1
28	Sulawesi Selatan	6,792	2.9	1.4
29	Sulawesi Tengah	1,444	5.3	2.9
30	Sulawesi Tenggara	1,208	7.5	3.9
31	Sulawesi Utara	2,116	1.7	0.9
32	Sumatera Barat	3,897	0.5	0.3
33	Sumatera Selatan	6,038	0.9	0.4
34	Sumatera Utara	12,719	0.6	0.3

Table C-3 Water Consumption Coverage Potential – 5% Water Occupancy

No	Province	Yearly Water Consumption [thousand m^3]	Coverage [%]
1	Aceh	55,892	0.71
2	Bali	159,537	0.05
3	Banten	240,019	0.11
4	Bengkulu	24,721	1.22
5	DI Yogyakarta	47,283	0.04
6	DKI Jakarta	494,518	0.05
7	Gorontalo	21,923	0.36
8	Jambi	49,133	0.44
9	Jawa Barat	419,502	0.17
10	Jawa Tengah	485,528	0.10
11	Jawa Timur	721,847	0.10
12	Kalimantan Barat	76,056	0.73
13	Kalimantan Selatan	113,124	0.17
14	Kalimantan Tengah	42,652	0.63
15	Kalimantan Timur	199,261	0.25
16	Kalimantan Utara	24,251	0.10

No	Province	Yearly Water Consumption [thousand m^3]	Coverage [%]
17	Kepulauan Bangka Belitung	8,725	2.88
18	Kepulauan Riau	94,092	0.75
19	Lampung	17,520	0.76
20	Maluku	9,618	3.63
21	Maluku Utara	28,191	1.30
22	Nusa Tenggara Barat	80,591	1.76
23	Nusa Tenggara Timur	34,586	1.06
24	Papua	5,724	469.92
25	Papua Barat	20,698	43.95
26	Riau	18,467	0.76
27	Sulawesi Barat	9,465	0.03
28	Sulawesi Selatan	146,838	0.52
29	Sulawesi Tengah	23,269	1.66
30	Sulawesi Tenggara	15,439	2.64
31	Sulawesi Utara	29,760	0.60
32	Sumatera Barat	109,266	0.07
33	Sumatera Selatan	197,242	0.08
34	Sumatera Utara	325,447	0.11