HYDROPOWER POTENTIAL IN INDONESIA

ASSESSMENT OF THE THEORETICAL, TECHNICAL AND ECONOMIC POTENTIAL OF HYDROPOWER

Citra Septa Permata

Master of Science Thesis

TU Delft

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ASSESSMENT OF THE THEORETICAL, TECHNICAL AND ECONOMIC POTENTIAL OF HYDROPOWER

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Acknowledgement

This thesis marks the end of my study in Water Management at TU Delft, a place I once called a dream. Pursuing master's degree and living abroad is a valuable experience which broadens my knowledge not only related to academics but also lessons of life. A lesson which taught me that while chasing my dream, I must learn how to survive, how to stop and how to get back on my feet. Despite all of the turbulence, I am overjoyed to have crossed the end of my study and would like to express my deepest gratitude to everyone who has helped and supported me along the journey.

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For my parents, my country and myself.

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Abstract

Indonesia has a severe problem of fossil fuel dependency, making it become one the world's larger carbon emission contributor. At the same time, the growing population will increase the energy demand in the future. Thus, in order to meet the energy demand and decrease the carbon emission, the government together with PLN as the state electricity company will committed to implement carbon neutral targets by 2060. Additional of 413 GW installed power capacity will be necessary in which 308 GW generated from renewable energy[1]. Indonesia has many renewable energy alternatives that can be utilized such as solar, wind, biomass, and hydropower. Among various renewable energy alternatives, hydropower has emerged as one of the means to achieve the aforementioned targets. Indonesia has a hydropower potential of around 75 GW from large hydropower and 19.4 GW from small hydropower[2], meanwhile, due to a number of barriers, hydropower contributed only 7% from installed large-scale hydropower and 2% from installed small-scale power plants[2,3].

In order to reach the government's goals, further study is needed to better understand the hydropower potential in Indonesia. Hence, the aim of this research is to quantify the potential of hydropower for Indonesia to find the possible location based on the economic consideration and to understand the positive influence of hydropower application. The analyses will be done using GIS-based modelling approach based on three DEM sources with 3 different resolutions, namely DEMNAS (0.27 arcseconds), USGS (1 arcsecond) and MERIT (3 arcseconds). The gross theoretical potential will be calculated based on the river discharge and the head of every pixel of the DEM. Further, the technical potential could be obtained by eliminating the output of theoretical potential with contraints area. Subsequently, the cost components (e.g investment and operational cost) will be added to the model to quantify the levelized cost of electricity (LCOE). The potential location that has LCOE lower the cost of power generation.

Based on the analysis, the theoretical potential in Indonesia ranges for approximately 159 GW to 182 GW, or in annual energy production amounts to 1400 TWh to 1600 TWh. Subsequently, the technical potential after eliminating the constraints area decreased to around 550 TWh (63 GW) – 700 TWh (80 GW). On the other hand, based on the technical potential results, the LCOE ranges from 1 to 69 cent USD/kWh. However, only around 45% of the total technical potential is economically feasible. Thus, the hydropower potential lowered to 240 TWh (10 GW) – 690 TWh(38 GW). According the results, hydropower could cover 9% to 25% of the total required additional capacity planned by PLN and could reduce the carbon emission around 90% compared to the carbon emission of fossil fuels. Since this study used three different DEM resolutions, the output of the analyses varies depending on the DEM used. Based on the results, higher resolution DEM could delineate river shape better and thus the location of estimated hydropower potential location could be more accurate. However, DEM with larger pixel size could detect better the medium and large hydropower potential

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[1] Aristi, S. (2022, August 31). PLN Siapkan Mitigasi Perubahan Iklim Seiring Pencapaian Target Carbon Neutral pada 2060. PT PLN (Persero). https://web.pln.co.id/cms/media/siaran-pers/2022/08/pln-siapkan-strategi-mitigasi-perubahan-iklim-seiring-pencapaian-target-carbon-neutral-pada-2060/

[2] Asian Development Bank [ADB] & Asian Development Bank. (2020). *Indonesia Energy Sector Assessment, Strategy, and Road Map - Update*. Asian Development Bank. https://www.adb.org/sites/default/files/institutional-document/666741/indonesia-energy-asr-update.pdf

[3] Langer, J., Quist, J., & Blok, K. (2021). Review of Renewable Energy Potentials in Indonesia and Their Contribution to a 100% Renewable Electricity System. *Energies*, *14*(21), 7033. https://doi.org/10.3390/en14217033

List of Abbreviation

BP	British Petroleum
BPP	*Biaya Pokok Penyediaan Pembangkitan* (Cost of power generation for electricity provision by PLN)
BPS	Badan Pusat Statistik (Central Bureau of Statistics)
CAPEX	Capital Expenses
COE	Cost of Energy
CF	Capacity Factor
CRF	Capital Recovery Factor
DEM	Digital Elevation Model
FAO	Food and Agriculture organization
GIS	Geographical Information System
HPP	Hydropower Plant
IAEA	International Atomic Energy Agency
IEA	International Energy Agency
IESR	Institute for Essential Services Reform
IPPKH	Izin Pinjam Pakai Kawasan Hutan (Borow-to-Use Forestry Permit)
MEMR	Ministry of Energy and Mineral Resources
MoEMR	Ministry of Energy and Mineral Resources
MTOE	Tons of Oil Equivalent
LCOE	Levelized Cost of Energy
NPV	Net Present Value
OPEX	Operational Expenses
PLN	State Electricity Company
QGIS	Quantum Geographic Information System
RE	Renewable Energy
RI	Republik Indonesia (Republic of Indonesia)
USGS	United States Geological Survey

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1 | Introduction

1.1 Indonesia's future targets

The reliance on fossil fuels is a major issue in Indonesia. Around 50% of the total energy for electricity generation comes from coal production, reaching 616 million tons in 2019 (MoEMR, 2020). The carbon emission from coal production has negative consequences for the environment, and due to the excessive electricity generation from coal, Indonesia has become the 10th largest CO_2 emissions emitter globally (BP Global, 2019). Therefore, Indonesia set a goal to comply with the Paris agreement by reducing greenhouse gas emissions by 29%, and 41% through international cooperation (Witoelar, 2016). Moreover, PLN, as the state electricity company, also committed to implementing net zero emissions by 2060 (Santikaaristi, 2022).

Another goal is the government's target of making the country the fifth-largest economy globally by 2045 (Listiyanto & Pulungan, 2021), where energy security and infrastructure development are two of eleven sectors to be improved from the sustainable economic development plans. Infrastructure development will be carried out to balance the high standard of living and the rapid population growth, which is expected to increase by 33% in the next 24 years (BPS RI, 2018). In order to achieve carbon-neutral targets and to meet the future electricity demand, renewable energy sources will be increased to 23 percent by 2025 (President Regulation No. 22, 2017) and PLN plans to install additional 413 GW power capacity, with 75% (308 GW) is generated from renewable energy resources (Santikaaristi, 2022).

1.2 Utilization of hydropower in Indonesia

Indonesia has many renewable energy alternatives that can be utilised to achieve Indonesian economical targets, such as solar, wind, biomass, and hydropower. According to Irena, in 2019, electricity generation from renewable energy (RE) accounted for approximately 13% of the total 62.8 GW of electricity production (ADB, 2020), which is still below the government target to reach renewable energy mix of 23% by 2025 (President Regulation No. 22, 2017). Among the numerous renewable energy options, developing hydropower could be one of the means to attain the aforesaid goals, as Indonesia has a hydropower potential of around 75 GW from large hydropower and 19.4 GW from small hydropower (National General Energy Plan, 2017). However, from the total electricity generation capacity (62.8 GW) in 2019, hydropower contributed only 7% from installed large-scale hydropower and 2% from installed small-scale power plants (ADB, 2020; Langer et al., 2021).

Currently, hydropower in Indonesia has not been fully optimised and according to Institute for Essential Services Reform (IESR, 2018), Included among the obstacles are financial, awareness, regulatory uncertainty, infrastructure, skilled workers, and public acceptability. Moreover, there is still a need for more in-depth research regarding the optimal location and the economically viable potential of hydropower throughout Indonesia.

1.3 Problem statement and research objectives

Indonesia's total hydropower potential was discovered to be 75 GW (National General Energy Plan, 2017), as mentioned in the previous section. Nevertheless, the number was estimated without taking economic potential into account; therefore, this study will include a more in-depth examination of the theoretical, technical and economic potential of hydroelectric energy in Indonesia.

The first part of the analysis is to quantify the theoretical hydropower potential to find the gross hydropower potential in Indonesia. The following assessment evaluates the technically feasible potential by considering several constraints area, assuming the future application of hydropower, while economic potential analysis includes several cost components calculations and the social enticing. There is no study that thoroughly assesses these potentials for hydropower in Indonesia to the author’s knowledge.

The main objective of this research is to estimate the technical and economic potential of hydropower in Indonesia and to understand the contribution of hydropower utilisation to national electricity generation and CO_2 emission. The objective is split into four sub-objectives, where the first, second and third aim to identify the theoretical, technical and economic potential, respectively. Finally, the last sub-objective is to investigate the impact of hydropower on the emitted carbon emission from electricity generation.

1.4 Research question

This thesis assesses the potential of hydropower in every province in Indonesia. The aims are to quantify the potential of hydropower for Indonesia in order to find the possible location based on the economic consideration and to understand the positive influence of hydropower application.

Based on this objective, the main research question can be formulated as follows:
What is the hydropower potential throughout Indonesia and the contribution of its utilisation?

In order to help in answering the main research question, several sub-questions arise:

1. What is the theoretical potential of hydropower in Indonesia?
2. What is the technical potential of hydropower in Indonesia?
3. What is the economic potential of Hydropower in Indonesia?
4. How much CO_2 emissions could be reduced from hydropower utilisation?

1.5 Research approach

The research approach for this thesis is to assess the theoretical, technical and economic potential of hydropower using a spatial modelling approach, considering the amount of data required and the duration limitation of this study. The modelling will be performed using geographic information system (GIS) to allow spatial datasets management and analysis, improving and removing errors from the data, performing calculations and visualising results in geographical figures (Romanelli et al., 2018). Hence, GIS is chosen for the reason that it is proficient at handling geospatial data management and able to generate detailed potential analysis (Blok & Nieuwlaar, 2020) which is also the primary intention of this research.

In order to answer the first and the second parts, the theoretical and technical potential assessment will be conducted. Theoretical potential of hydropower would be obtained using GIS as the tool to process the topography and runoff data into a theoretically feasible location together with the amount of energy that could be generated in that specific location. The outputs of gross potential analysis, which will be hydropower locations and the power generated, will be further used as the basis for classifying the type of hydropower and as the input for technical potential analysis. Several constraints criteria will be included to define the location with promising hydropower location.

The next analysis will be the economic potential to answer the third sub-question, which is related to the second and third sub-questions. This step results in geospatial economic potential data that is indicated by LCOE. The LCOE will be the average cost of energy generation per kWh that is achieved from the total amount of construction and operation cost of hydropower over the energy produced per year or the technical potential from the previous analysis. The estimated cost components used in the formula are based on grey literature reviews or academic publications. At last, the values from LCOE itself will be compared to the BPP (cost of power generation of electricity supplied by PLN)

Subsequently, in the fourth sub-question, the percentage of CO_2 emissions that could be reduced by hydropower utilization can be assessed through desk study based on the results obtained from all of the previous sub-questions compared to the CO_2 emission from fossil fuels.

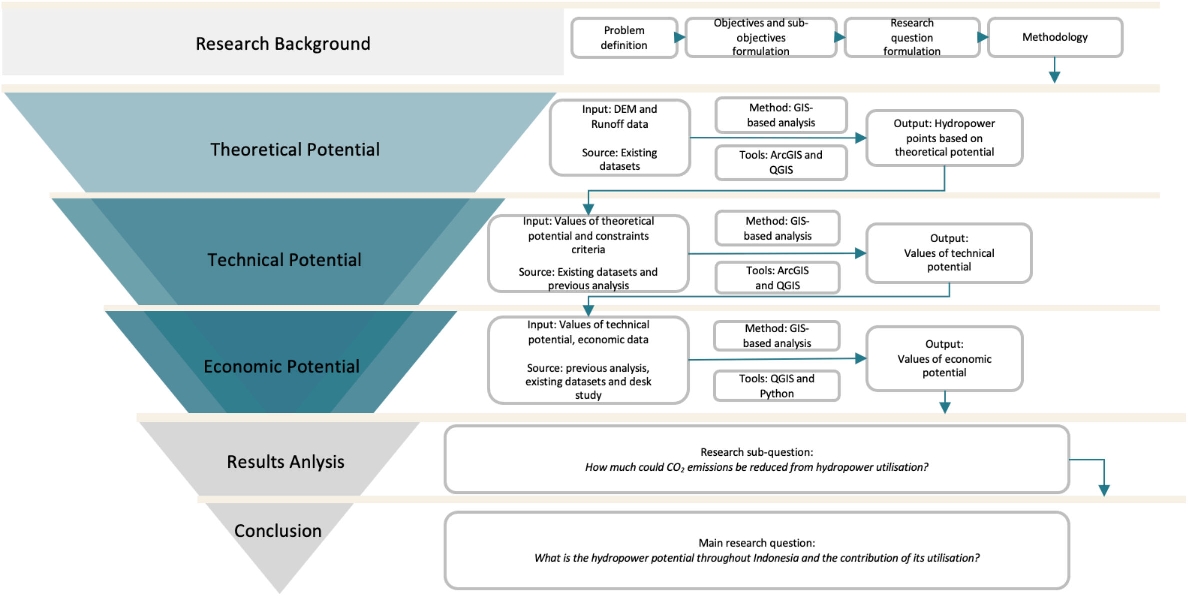


Figure 1 Research flow diagram

1.6 Thesis outline

This report is divided into six chapters. The first chapter is the introduction part which consists of background explanation, problem statement, research question and research approach. Chapter 2 will explain the insights from the literature review and Chapter 3 will explain the theoretical background. Followed by Chapter 4 which describes about the methodology for theoretical, technical and economic potential analyses. The results of all analyses will be discussed in Chapter 5. Finally, the conclution, limitation of study and future research recommendation will be discussed in Chapter 6.

2 | Literature Review

In this chapter, relevant literature reviews on the technical and economic potentials of hydropower in Indonesia will be addressed. First, in chapter 2.1, the concept of potential will be explained, and then in chapter 2.2, the findings of the literature review will be discussed.

2.1 Potential as a concept

The evaluation of hydropower potential begins with a classification of the varying kinds of potential. According to Blok and Nieuwlaar (2020), the potential is defined into six distinct types. These types are referred to as theoretical potential, technical potential, economic potential, profitable potential, market potential, and policy-enhanced potential. In this literature review, three types of potential (theoretical potential, technical potential and economic potential) were considered as an ideal conditions to define the potential of hydropower. Therefore, these three types of potential are the main focus of this literature review. According to Hoes (2017), the theoretical hydropower potential or gross potential shows the total amount of electricity generated that could be obtained when all available water resources were utilized for hydroelectricity. However, the theoretical potential is not applicable in the real situation as several factors, such as seasonal river discharge and turbine efficiency, could influence the electricity generated from the hydropower plant. The technical potential expresses the exploitable hydropower capacity that is attractive and obtainable with existing technology. Technical potential takes into consideration the technical constraints when connecting the hydropower to the existing power grid, resulting in a more realistic selected location of hydropower (Blok & Nieuwlaar, 2020; Breeze, 2019). Lastly, the economic potential is the economically exploitable amount of capacity generated from hydropower, which could be constructed after performing a feasibility study on each site at current prices and obtaining a favourable result (Hoes et al., 2017).

2.2 Hydropower potential analysis from other studies

There is a need for a hydropower potential study because of the opportunity for this renewable energy technology to benefit local populations through the provision of greener, low-cost electricity (Korkovelos, 2018). There have been a number of studies that have evaluated the theoretical, technical and economic potential of hydropower. Several studies conducted theoretical potential analysis for hydropower. The potential is estimated using GIS-based modelling, requiring Digital Elevation Model (DEM) to determine the river flow direction and flow accumulation and runoff data as the weighted raster to create the river discharge (Dim et al., 2017; Hoes et al., 2017; Hoes et al., 2014; Meijer et al., 2014; Tefera and Kasiviswanathan, 2022). The hydropower capacity then will be calculated based on the elevation drop (H) and river discharge. According to Tefera and Kasiviswanathan (2022), the theoretical potential assessed by neglecting the overall efficiency (η) and capacity factor (CF) unlike the technical potential.

Some studies determine the technical potential by adding constraints area (e.g. distance-to-power line maps). Tefera and Kasiviswanathan (2012), calculated the total technical hydropower potential by eliminating the result of estimated theoretical potential using allowable waterway length, and further, non technical aspects (i.e. protected land and dense residents) will be included to eliminate the potential. Meanwhile, Gernaat et al. (2017) created a distance map of each cell to the basin outlet to identify the technical hydropower potential at every 25 km river interval. Different from previously mentioned studies, Zhou et al. (2015) quantify the technical potential based on head and monthly river discharge, taking into account practical design concern and the assumption that 30% of monthly river flow will surpass the turbine's design capacity preventing power generation.

There are several ways to obtain the economic potential, for example using site specific cost estimation derived from mathematical expression of least squares fitting curve (LSFC) and existing cost data for the turbine (Gernaat et al., 2017; SWECO Norge AS, 2012; Hall et al., 20013). Another method is by calculating the cost of energy (COE) which takes into account the development cost of hydropower as well as the operation and maintenance cost (Zhou, et al., 2015), different from levelized cost of energy (LCOE) that use discount rate for the calculation, COE use only fixes price rate. Study of Kumara et al., (2014) used Net Present Value (NPV) and investment analysis for their economic potential, and cost variables that influence NPV include total initial investment, operation and maintenance, annual energy sales, interest rate, and life time of the plant. Meanwhile, this research will use LCOE to derive the economic potential that is also used by (Langer et al., 2020; Bocchiola et al., 2020 and Wahyuono and Julian, 2018).

Table 1 shows the lists of literatures reviewed in this section. Although there are some studies that discussed about hydropower potential Indonesia, there is only limited information that covers the hydropower potential for the entire islands in Indonesia. For instance, studies of Rosprianda and Fujii (2017) and Kumara et al. (2014) examined only for Bandung and Bali, respectively. Unlike the others, study of Wahyuono and Julian (2018) covers the hydropower potential for entire parts of Indonesia. However, that research conducted only the gross potential without taking into account the technical concerns and economic potential. A study from Gernaat et al. (2015) evaluates every 25 km interval of any river between 56° S and 60° N using technical and economic potentials; however, Indonesia is not included. Moreover, using 25 km as an interval could lead to overestimate or underestimate result as the discharge of the river oftentimes is constant due to unstable velocity. Furthermore, most studies used only one DEM source without explaining the reason for the selection. Considering the research gap, where the theoretical, technical and economic potential of hydropower in Indonesia remains underexplore and the comparison between DEM data used within the analyses are not discussed in most studies, the additional insight in this particular area is expected to fill the gap.

Table 1 Analysis of hydropower potential studies

Author (year)	Geographical scope (Location of study)	Type of Hydropower	Data source	Potential Indicators			
				Theoritical	Technical	Economic	
				P	P	LCOE	Other
Dim et al (2017)	Myanmar	All	USGS HydroSHED (DEM) UNH-GDRC (runoff data)	v			
Hoes et al (2017)	Global	All	GMTED2010 (DEM) UNH-GRDC (composite runoff data)	v			
Gernaat et al (2017)	Global*	-	HydroSHEDS (hydrographic maps and topographic data) LPJmL (hydrology and vegetation model)		v		v
Zhou et al (2015)	Global*	-	HydroSHEDS (hydrological data and maps)	v	v		v
Hoes et al (2014)	East Asia	All	USDS HydroSHEDS (elevation data) Global Runoff Data Center (global runoff)	v			
Meijer et al (2014)	Global*	All	HydroSHEDS (DEM and DIR) UHN-GRDC (runoff data)	v			
Rospriandana and Fujii (2017)	Bandung, Indonesia (Ciwidey watershed)	Small	USGS Earth Explorer (DEM) Geospatial Information Agency of Indonesia (land use) Water Resources Agency of West Java (daily precipitation and river discharge)	v			
Wahyuono and Julian (2018)	Indonesia	All	CRU (climate data) GLCNMO (land cover) DEM (SRTM)	v			
Kumara et al (2014)	Bali, Indonesia	Micro	Department of Public Works (river flow rate) Google earth (contour data)	v			v
Bocchiola et al (2014)	Nepal (Dudh Koshi Basin)	-	ASTER GDEM (Topography, DEM and meteorological data)		v	v	
Farinotti et al (2019)	Antarctic	Large	GloCEM (basin runoff)		v	v	
Casale et al (2020)	Afghanistn (Kabul river)	-	Agriculture Research Department-Meteorogical Department FAO Pakistan Meteorogical Department		v		
Tefera and Kasiviswanathan (2022)	Global (90°N-60°S)	All	MERIT (DEM) Runoff (Ghiggi et al., 2022) Global dams and reservoirs datasets (SEDAC)	v	v	v	

*only from 56° S to 60° N.

3 | Theoretical Background

Based on literature review of scientific publications, this chapter will introduce some theoretical background concepts. Section 3.1 will provide an overview of hydropower technology and methods. Section 3.2 will classify hydropower classification based on operation and flow type. Lastly, in order to calculate LCOE, the cost components of hydropower plants are discussed in section 3.3.

3.1 Technology of Hydropower

Hydropower is an electricity generator that exists as potential energy converted into kinetic energy, through the flow of precipitation collected in the rivers to the oceans, and thus could activate the turbine to produce electricity. Generally, hydropower has been recognized for its status as a clean, cheap, renewable energy alternative that uses proven technologies. Hydropower, like other renewable energy sources, is expected to have low operational costs and long life once installed, especially for run-of-river and reservoir projects where sedimentation is not an issue (Mirza et al., 2008). As water travels down a penstock or channel, it reaches a waterwheel or turbine, where it would turn the shaft by striking the wheel's bucket. When producing electricity, a rotating shaft attached to a generator turns shaft motion into electrical energy (Manzano-Agugliaro et al., 2017). The hydropower produced from the potential energy of water drives turbines to create electricity, as seen in Figure 2. The capacity and head between down and up streams determine the amount of energy that can be recovered from water. (Elbatran et al., 2015).

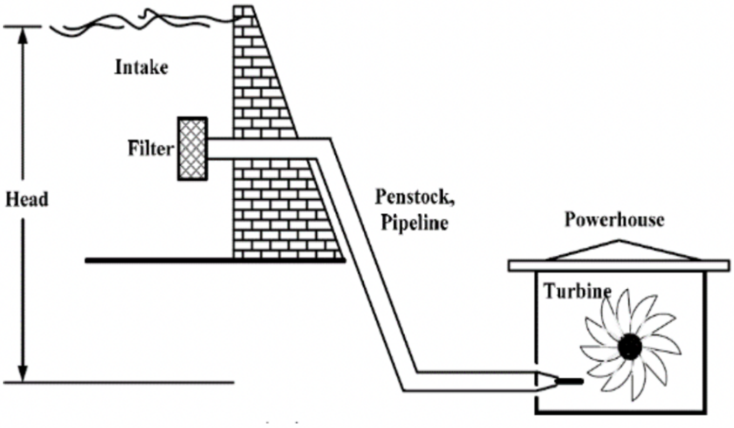


Figure 2 Power generation in Hydropower (Elbatran et al., 2015).

The existence of hydropower technology has an influence on the surrounding ecosystem and environment. Von Sperling (2012) explained that the installation of hydropower plants has both positive and negative impacts. On the positive side, hydropower plants could contribute to the reduction of greenhouse gas emissions since they do not burn fossil fuels and do not create carbon dioxide directly, also hydropower is a cheap energy source. Furthermore, the formed reservoir made by hydropower plants may be utilized for irrigation functions, which will be beneficial for farmers or agricultural purposes in Indonesia.

The installation of hydropower technology also has downsides to the ecosystem or the surrounding. Chen et al. (2015) indicate that damming has resulted in significant ecological changes, such as the changes in river structure. According to Von Sperling (2012) the temperature of the river will be affected by the temperature of the reservoir's outflow. This may influence the plant and animal life in both the reservoir and the river since water flows downstream. Moreover, the dams from the hydropower plants could stop fish from going to spawning areas, which could threaten the species population in the area downstream. Fortunately, this problem can be fixed by doing things like installing fish ladders.

3.2 Classification of Hydropower

According to Energy.gov (n.d), Hydropower Plants (HPP) are divided into three classifications based on the operation and flow type and are used for distinct condition and implementation. First, storage hydropower HPP which typically has a size of large hydropower that stores water in the reservoir and could provide energy during the peak demand. This type of HPP provides functions not only for energy generator but also other facilites, for instance, flood control, tourism and irrigation (Energy.gov, n.d). Another type is pumped storage hydropower (PSH), which capable of storing electricity generated by alternative energy sources such as solar, wind, and nuclear by pumping water from a storage at a lower elevation to the higher one. The thirds type is Run-of-the-River hydropower (RoR HP), the hydropower plant that has no or limited reservoir, and depends on the fluctuating seasonal flow of the river. This type of hydropower, therefore, provides a discontinuously energy sources. In RoR HP, a part of the river flow will be directed to penstock or pipe line that further will be transported to hydraulic turbine attached to the generator.

Besides classification based on the operation, hydropower also classified into 6 types based on the size depending on its capacity. The definition of the type may vary in every country, for instance, hydropower below 10 kW might be classified as pico in some countries, or in another country there is only three types of hydropower (micro, medium and large HPP). Nonetheless, for this study, the sizes are ranging from pico to large and can be seen in Table 2.

Table 2 Types of hydropower generation

Hydropower type	Capacity
Large	> 100 MW
Medium	15 – 100 MW
Small	1 – 15 MW
Mini	100 kW – 1 MW
Micro	5 kW – 100 kW
Pico	< 5 kW

3.3 Cost components of hydropower plants

Cost components are important variable to quantify Levelised Cost of Elctricity (LCOE). Several cost components of hydropower (i.e several variables are needed, namely CRF, CAPEX, OPEX, and E_t) will be explained below.

Capital Expenditures (CAPEX)

The costs of civil engineering projects (dam, reservoir, penstocks, tunnels, power house), powerhouse equipment, roads, transmission lines, and other costs such as planning, management, approval, etc are included in the main capital expenditures (CAPEX) for hydropower plants (Godyn et al, 2015). Large-scale hydropower project total installed costs generally vary from roughly USD 1000/kW to around USD 3500/kW (IRENA, 2012). However, projects with expenses that exceeding this range are not uncommon. Installing hydropower capacity at an existing dam that was constructed for other functions (flood control, water provision, etc.) could cost anywhere from $500/kW. Projects in remote locations, on the other hand, with inadequate local infrastructure and located far from existing transmission networks, may cost significantly higher than USD 3500/kW.

Operational Expenses (OPEX)

Over their lifespan, hydropower plants have low operating costs, and large-scale hydropower plants have lower OPEX costs than small and micro plants. Annual OPEX are typically expressed as a percentage of the initial investment cost (Godyn et al, 2015). The typical range is from 1% to 4%. Some authors break down OPEX into fixed (commonly in a currency unit per kW) and variable costs (usually in a unit of currency per MWh). The normal range is from 1% to 4%. The IEA estimates 2.2% for large hydropower projects and 2.2% to 3% for smaller projects, with a global average of about 2.5% (IEA, 2010c/NO 3).

Capital Recovery Factor (CRF)

The present value of an annuity is calculated using the capital recovery factor (Xu et al, 2020). The CRF is defined as the annual cash flow that must be generated depending on project duration (e.g. 30 years of project duration) in order for the present value of the cumulative cost to equal one unit of money. Project length (in years) and the discount rate are needed in order to define the CRF (Patel and Singal, 2016).

Levelized Cost of Electricity

The Levelized cost of electricity approach (LCOE) is commonly used to assess the average total costs of electricity generation (Godyn et al, 2015). The LCOE covers the costs of construction and operation over the project's lifetime. It also reflects the energy break-even point (Aldersey-Williams & Rubert, 2019).

4 | Methodology

This chapter will provide the methods used for theoretical, technical and economic potential analyses based on GIS-based approach, which the chosen approach will be explained in Section 4.1. Next, the calculation methods for theoretical, technical and economic potential will be discussed in Section 4.2, Section 4.3 and Section 4.4, respectively.

4.1 GIS-based approach

This approach was chosen to assess the theoretical, technical and economic potential of hydropower. GIS was used as the tool to process the topography and runoff data into theoretically feasible locations together with the amount of energy that could be generated in that specific location. GIS enables the analysis of georeferenced data in various directions and visualize the information with various options of color schemes and symbols (Huisman & By, 2009; Arán Carrión et al., 2008). In addition, The GIS has shown beneficial in enhancing hydropower development in Brazil, Turkey and Korea, by offering the site selection of priority locations with minor constraints (Romanelli et al., 2018; Kucukali et al., 2021; Yi et al., 2010) Hence, GIS is chosen for the reason that it is proficient to handle geospatial data management, able to generate detailed potential analysis and is proven as a highly effective instrument to assist decision-makers in developing, evaluating and implementing hydroelectric plants (Blok & Nieuwlaar, 2020; Romanelli et al., 2018) which is also the primary intention of this research. ArcGIS and QGIS were used to process the input data and to perform the analyses.

4.2 Theoretical potential

This section will explain about the input data and the calculation methods for theoretical potential analysis in different subsections.

4.2.1 Input data

The Digital Elevation Model (DEM) data used in this study are retrieved from DEMNSA, USGS and MERIT with resolution of 0.27 arcseconds, 1 arcsecond and 3 arcseconds, respectively. Since Indonesia is located at the equator, the resolution of these sources in meter are ± 8 m (DEMNAS), ±30 m (USGS) and ±90 m (MERIT). Modifications in the DEM and several improvements such as sink removal and gap-filling interpolation have been carried out.

The runoff data is taken from the UHN-GRDC Composite Runoff Fields V1.0 dataset. The data set is a monthly average with 30 minutes spatial resolution, and is derived from measurements of river discharge and a climate-driven Water Balance Model. According to Fekete et al. (2014), Hoes et al. (2017) and Meijer et al. (2012), According to Fekete et al. (2014), Hoes et al. (2017) and Meijer et al. (2012), Runoff data could be used and considered most ideal to estimate the discharge since the discharge measurement period varies depending on the gauging station and precipitation varies over time in every location.

4.2.2 Calculation method and selection criteria

For this step, the gross capacity of hydropower can be calculated using the following equation:

$$P = \rho \cdot g \cdot H \cdot Q \qquad (1)$$

Where P is the hydropower capacity (W), ρ is the density of water (kg/m^3), g is the gravitational acceleration (m/s^2), H is the head (m), and Q is the discharge (m^3/s). For gross theoretical potential, the turbine and capacity factor will be neglected and will be assumed that maximum annual energy is obtained as 100% of annual runoff is used in the energy production by the hydropower.

This research used elevation data to delineate a river network for each cell in raster data of Digital Elevation Model (DEM). Two GIS algorithms were used, which are flow direction and flow accumulation along the process to produce the average annual river discharge. The runoff data (mm/month) as the weighted factor is multiplied by the flow direction in order to define the accumulated runoff for each raster cell which further will be converted into river discharge (m^3/s). As a result of this calculation, river discharge maps of each pixel with the resolution of 3 arcsecond, 1 arcsecond and 0.27 arcsecond were produced.

In a subsequent step, the accumulated discharge of ever cell will be filtered by minimum discharge (Qmin). Input variable Qmin is the minimum discharge required to consider whether a grid cell has sufficient discharge. It is important to determine the suitable Qmin value that is likely that the surface runoff occurs so that there will be no discharge of interest are overlooked. Thus, the minimum discharge chosen for the selection criteria is Qmin of 0.1 m^3/s. Moving to a further step, slope calculation was executed concerning only the elevation of river grid cell towards its upper and lower neighbours. Also, river DEM map is created from elevation map and discharge, the elevation value will be assigned in where the discharge is higher than 0.1 m^3/s. As a result, a map contains slope of each grid of river DEM is obtained and further will be multiplied by the length of each cell to determine the head in each river cell.

Other than Qmin, another variable that has to be considered is Hmin, which is the minimum head of interest that is required for the development of hydropower. Basically, the minimum head is determined by the type of turbine, the low-head turbine in specific. Low-Head turbines deal with a head in the range between 2 m and 35 m (Meijer et al., 2012; Krompholz, 2008). Pixels with higher head differences will have greater feasibility for hydropower plant location. However, since pico and micro hydropower will also be considered in this research, sensitivity studies proclaimed that head less than 10 m tends to exclude pico and micro hydropower potential (Meijer et al., 2012), for DEM with 1 arcsecond and 3 arcseconds resolution a minimum head of 4 m per raster grid cell is selected.

The smallest potential will be 4 kW (with an annual energy generation of 35 MWh) from the combination of Qmin (0.1 m^3/s) and H min (4 m) calculated using equation 1. However, for 0.27 arcseconds DEM (pixel size of approximately 8 m x 8 m), the chosen Hmin is 0.5 m and the Qmin is 0.1 m^3/s. Later on, the hydropower capacity below 4 kW in calculation results will be excluded from the analysis. The Hmin is set to 0.5 m because 4 m slope in 0.27 arcseconds DEM (pixel of around 8 m by 8 m) will be too steep. Also, in some areas where the H is below 4 meters, the discharge is high enough to generate 4 kW hydropower capacity, in this case, if the Hmin is 4 m, then a lot of areas will be missed in the analysis. The methodology flow chart for theoretical potential analysis can be seen in Figure 2.

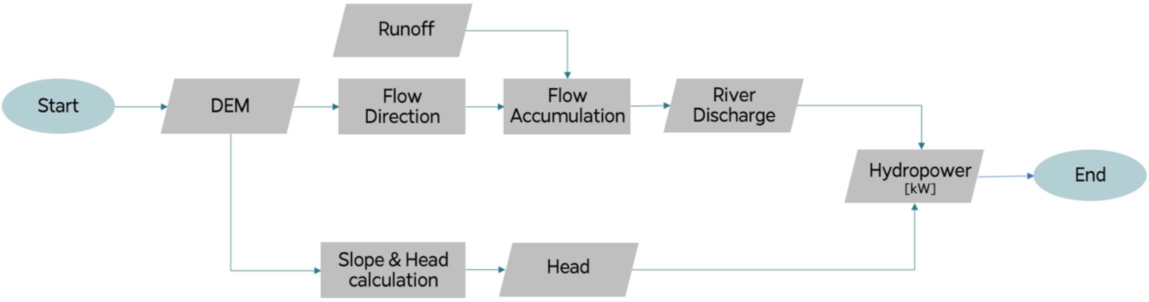


Figure 3 Methodology flowchart

The output from the last step in Figure 3 was vector points. In order to visualise the results into maps, the points data then will be converted into raster data which can be seen in Chapter 4.

4.3 Technical potential

This section will explain about the input data and the calculation methods for technical potential analysis in different subsections.

4.3.1 Input data

The outputs of gross potential analysis, which will be hydropower locations and the power generated, will be further used as the basis for classifying the type of hydropower and as the input for technical potential analysis. In the previous step, the calculation of theoretical potential did not include turbine efficiency as the main focus was on defining the gross potential. Facts of the matter, this efficiency factor is needed when estimating the power production per location since several losses are involved during the conversion of potential and kinetic energy of water to electricity. The efficiencies for hydropower turbines range between 60% and 90% (Meijer et al., 2012; Paish, 2002). In this study, seasonal change of discharge is not taken into account and annual average discharge will be used instead. The actual turbine efficiency is hard to estimate because it could be vary in each hydropower plant, however, the national hydropower capacity average efficiency of 70% is assumed here.

4.3.2 Calculation method and selection criteria

For this step, the technical potential can be calculated using the equation below:

$$P_2 = \rho \cdot g \cdot H \cdot Q \cdot \eta \cdot CF \qquad (2)$$

Where P_2 is the hydropower capacity (W), ρ is the density of water (kg/m^3), g is the gravitational acceleration (m/s^2), H is the head (m), Q is the discharge (m^3/s), η is the turbine efficiency (%) and CF is the capacity factor (-).

Due to technical, financial and environmental constraints, it is practically impossible to construct hydropower plants in all theoretically identified locations (Tefera and Kasiviswanathan, 2022; Moiz et al., 2018). As mentioned in Section 3.3.1, an additional factor was included in the calculation which is the efficiency factor (see Equation 2). After the hydropower capacity is obtained, additional criteria will be added in order to eliminate the unfavourable location by adding the technical and non-technical constraint areas.

According to the guideline book for hydropower potential study (2021) by PLN (Perusahaan Listrik Negara or State Electricity Company) and Hagos et al. (2022), there are three most important criteria for hydropower site selection—hydrological, topographical and geological condition. Other research also used GIS-based site selection criteria such as topography, hydrology, soils and social-economic (Hagos et al., 2022). The hydrological condition is already filtered during the theoretical potential analysis step when delineating the river discharge from runoff data. For topographical considerations, less steep location will be preferred, however, if the hydrological conditions are favourable then the area could still be considered for a hydroelectric power plant. Thus, in technical analysis, the geological aspect will be retrieved from FAO GeoNetwork. An area with unstable soil, expansive soil, clay loam, and soft organic soil will be included in the constraints. Other than these three criteria, it is also essential to check whether the area is accessible or not, otherwise, there will be difficulties in implementation and affect the economic potential. The existing grid map is also important to ensure sure there is a nearby grid to connect the hydropower to. However, the only data that can be downloaded is the transmission grid, which will not be used as a site selection criterion because the voltage is too high for pico, micro, and mini hydro. Moreover, the substation data from MEMR Geoportal are mostly concentrated in the western and central regions of Indonesia and are only a few substations in the eastern portion of Indonesia. Instead, the existing hydropower map from Energydata.Info is used to determine whether or not there are plants nearby.

4.3.3 Non-technical aspects

Hydropower as a renewable energy source may produce electricity without emitting greenhouse gases, but this does not imply that hydropower has no negative impacts on the ecosystem. Hydropower projects, whether large storage hydropower or even small hydropower, have the potential to negatively impact the natural ecosystem by disrupting habitats or inundating the area (EIB, 2019). Hence, non-technical constraints will be included in the analysis of this study to exclude protected areas. According to PLN guideline for hydropower potential study (2021) and Tefera and Kasiviswanathan (2022) and European Investment Bank (2019), several areas that are included in the constraints zone—including conservation of wildlife and natural habitats, and protected forest—and certain land use (residential, industrial, military, recreational area, private land use and cemetery). However, in this study protected forest will be separated from the constraints criteria since it is still possible to install pico, micro and mini hydropower with government permit or IPPKH (permit for borrowing to use the forest area).

Another matter to consider, Indonesia is prone to geological natural disasters such as tsunami earthquake, landslide, volcano, as it is located at the junction of three major tectonic plates (Cummins, P. R, 2017). Therefore, it is essential to include the natural disaster-prone area for this study. Maps of areas prone to tsunami, volcano and landslide from Infrastructure GIS of the Ministry of Public Works and Public Housing and earthquake-prone area from MEMR Geoportal are added to the constraints criteria.

4.4 Economic potential

This section will explain the input data and the calculation methods for economic potential analysis in different subsections.

4.4.1 Input data

In order to determine the economic potential, three essential data from the previous analyses are needed, namely the hydropower capacity (P), the head (H) and the annual energy production (Et). The head and hydropower capacity are required in the CAPEX calculation according to study of Tefera and Kasiviswanathan (2022), as can be seen in equation 4. For this calculation, the hydropower capacity refers to the installed capacity of the hydropower without considering the capacity factor. Meanwhile, the actual annual energy generation will be used in the LCOE calculation. The annual energy production can be obtained based on the rated hydropower capacity from technical potential analysis, where the capacity (in kW) will be converted to annual energy generated (in kWh).

4.4.2 Calculation method and selection criteria

In order to estimate the economic potential of hydropower, CAPEX, OPEX, and LCOE calculations will be conducted based on the study of Tefera and Kasiviswanathan (2022). In the first step of the process, the CAPEX (I_{cost}) will be calculated using equation 4, but the coefficient used to multiply the head variable is simplified to 1.8 since there is no explanation about the accuracy and error of this coefficient. The formula also requires the head and the hydropower capacity to determine the CAPEX. There are two cost coefficients in the equation, f and δ, where f (ranging from 5% to 10%) is the installation cost coefficient including interconnection of electromechanical, access roads and cost of development, and δ (with range of 0.8-2) is cost coefficient for electromechanical equipment. Due to the limitation of data gathering, the capital expenditure is estimated based on the formula below instead of the actual range of cost because it is strongly dependent on the site condition; investment costs in different sites may vary while having comparable head and capacity.

$$I_{cost}(million\$US) = 1.83024H^{-0.13}P_{3_{MW}}^{0.78}(1+\delta)(1+f)(US\$) \tag{4}$$

After the completion of the power plant's construction, it is expected that there will be a continuous supply of electricity. While the project operates, operations and maintenance facilities must always be maintained. Power plant capacity and investment cost both have a significant impact on OPEX (OM_{cost}). Thus, it would be calculated using equation 5, where there is one cost coefficient factor (μ) ranging from 1 to 4% (IRENA, 2012; Tefera and Kasiviswanathan, 2022). In this study, μ is assumed to be 3% (Tefera and Kasiviswanathan, 2022).

$$OM_{cost} = \mu I_{cost} \tag{5}$$

After obtaining the CAPEX and OPEX, the next step is to calculate the LCOE using equation 6. In order to understand the upper and lower cost boundary, there will be two scenarios of calculation based on CF (0.50-0.86), δ (0.8-2) and f (0.05-0.1). The first one (Scenario A) is combining the highest range CF with the lowest range of cost coefficient (δ and f) to obtain the lower cost with higher energy generated. On the contrary, the second scenario (Scenario B) combines the lowest range of CF with the lowest range of cost coefficients.

$$LCOE = \frac{CRF\ .\ CAPEX + OPEX}{E_t} \tag{6}$$

Where LCOE is the average total costs of electricity generation (USD ct/kWh), CRF is capital recovery factor (-), CAPEX is capital expenses (USD), OPEX is operational expenses (USD) and E_t is the electricity produced at year t (MWh).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{7}$$

Where i represent the interest rate (10%) and n refers to project lifetime (30 years)

The results of the calculated LCOE will be compared to BPP since the renewable energy sources tariff is determined from BPP (Langer et al., 2021). The hydropower location which LCOE is lower than or equal to BPP will be considered economically feasible. Finally, a sensitivity analysis will be done by quantifying the effect of changing parameters that determined the LCOE (e.g. CAPEX and OPEX) by raising and reducing the parameter by 20% relative to the LCOE.

5 | Results

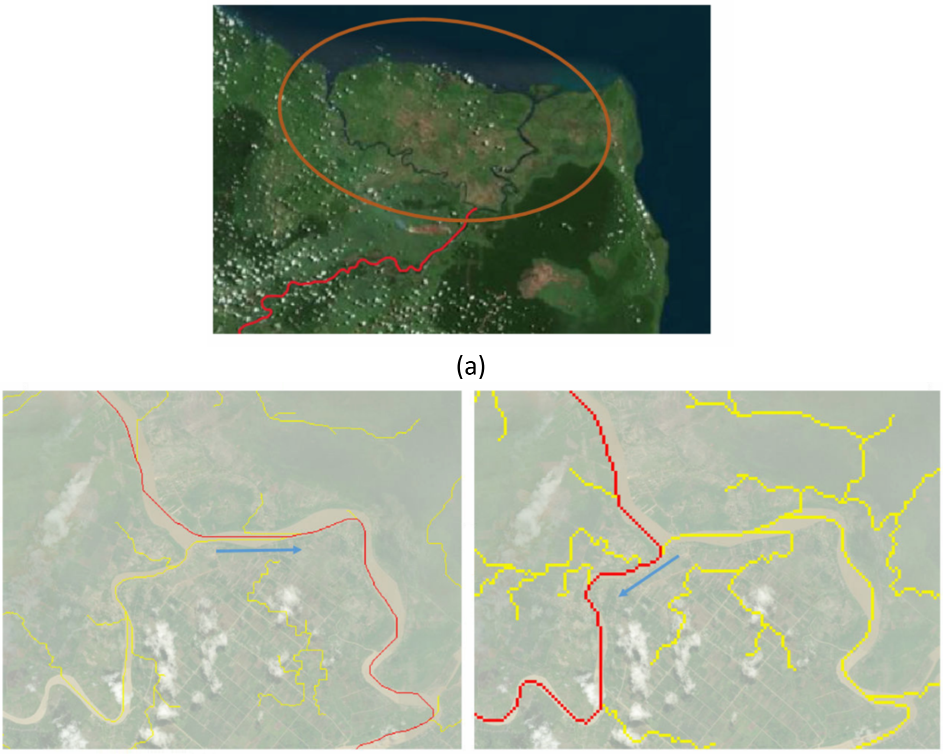
This chapter starts with theoretical potential in Section 5.1 which discusses the discharge simulation, spatial distribution and the results of the theoretical potential itself. Subsequently, Section 5.2 will provide the results of the technical potential analysis. Followed by the results analysis of economic potential in Section 5.3. Finally, the sensitivity analysis and validation will be explained in Section 5.4 and 5.5, respectively.

5.1 Theoretical potential of hydropower

This section will discuss the results of discharge simulation, spatial hydropower distribution and theoretical potential separately.

5.1.1 Discharge simulation

The river discharge is generated from the weighted flow accumulation of runoff. Since the flow direction algorithm is incapable of diverging flows, the simulation in deltas or artificial split-ups may be less accurate (see Figure 4). The impact on a delta's hydropower potential is insignificant because this bifurcation happens in practically all deltas' lower areas (with relatively small heads) that are unsuitable for hydropower development (Meijer et al., 2012).



(a)

(b) (c)

Figure 4 (a) Batang Hari river branch, (b) USGS result (c) MERIT result

In Figure 3, it is shown the difference between the result from USGS DEM and MERIT DEM. The red line is the Batang Hari river and the yellow line is the tributaries. In USGS result the river flows to the right branch, meanwhile, in MERIT result shows the contrary.

In addition, since the sources have different resolutions, in most of the parts, DEMNAS with a higher resolution (0.27 arcsecond) depicts a more similar river flow shape compared to USGS (1 arcsecond) and MERIT (3 arcseconds) with coarser resolution (see Figure 6). The reason is that the resolution ratio between DEMNAS and MERIT is 120 to 1, while DEMNAS and USGS have a resolution ratio of 14 to 1, meaning that 1 pixel in MERIT corresponds to roughly 120 pixels in DEMNAS, and 1 pixel in USGS corresponds to around 14 pixels in DEMNAS. Figure 6 also shows that DEMNAS could detect smaller streams as it has a higher spatial resolution, compared to USGS and MERIT which could mostly only the main channel. This might result in different hydropower potential locations and calculated capacity in theoretical and technical potential analysis results. Moreover, it has to be noted that the area near the estuary is usually flatter but DEMNAS could still delineate the river flow more precisely.

Figure 5 Aerial image of Ayung River, Bali

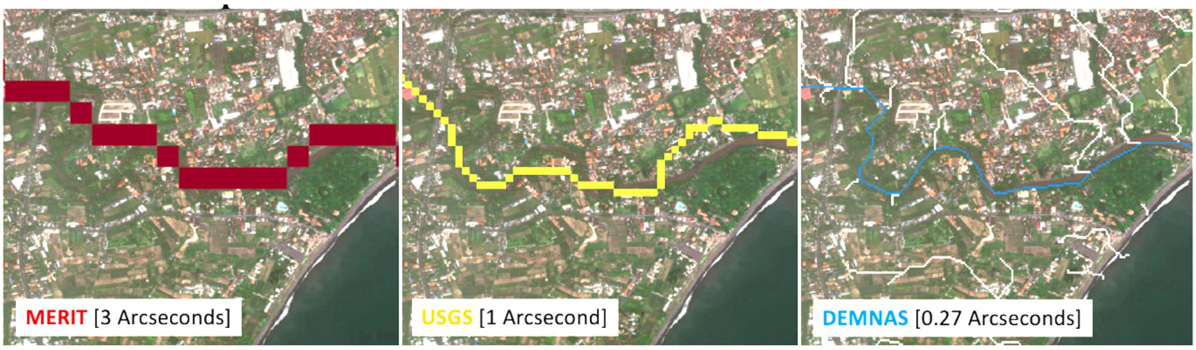


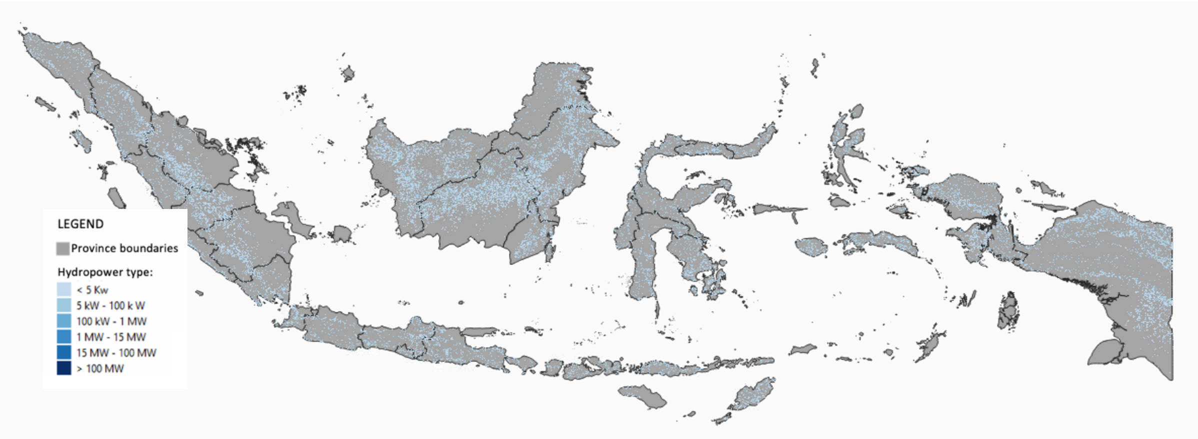
Figure 6 Comparison of river shape between USGS, MERIT and DEMNAS

Besides the shape, the discharge output from the three sources varies at the same location. As an instance, the river discharge at the location in the red circle in Figure 7 of DEMNAS is 10.8 m^3/s, 9.21 m^3/s for USGS, and 9.25 m^3/s for MERIT. The effect of the resolution on the river discharge is very site-specific, as in some places the estimation of the river basin area could be underestimated because in some parts of the area might be not included due to the limitation of the resolution.

Figure 7 River discharge located in red circle

5.1.2 Spatial hydropower distribution

The national spatial distribution of pico, micro, mini, small, medium and large hydropower from two different sources are presented in the figure below. It can be seen from Figure 8 and Figure 9 that the potential location for mini and small hydropower are higher for both USGS and MERIT results, followed by pico and micro hydropower, and the least one is medium and large hydropower. The reason is that although Indonesia has thousands of rivers, most rivers in Indonesia are small and short (Tang et al., 2019), so the construction of pico to small hydropower is especially suitable. The national spatial hydropower distribution from DEMNAS is not displayed because only three small islands will be calculated and will be hardly seen in figure, but the figure for the final analysis of DEMNAS can still be seen in section 5.3.

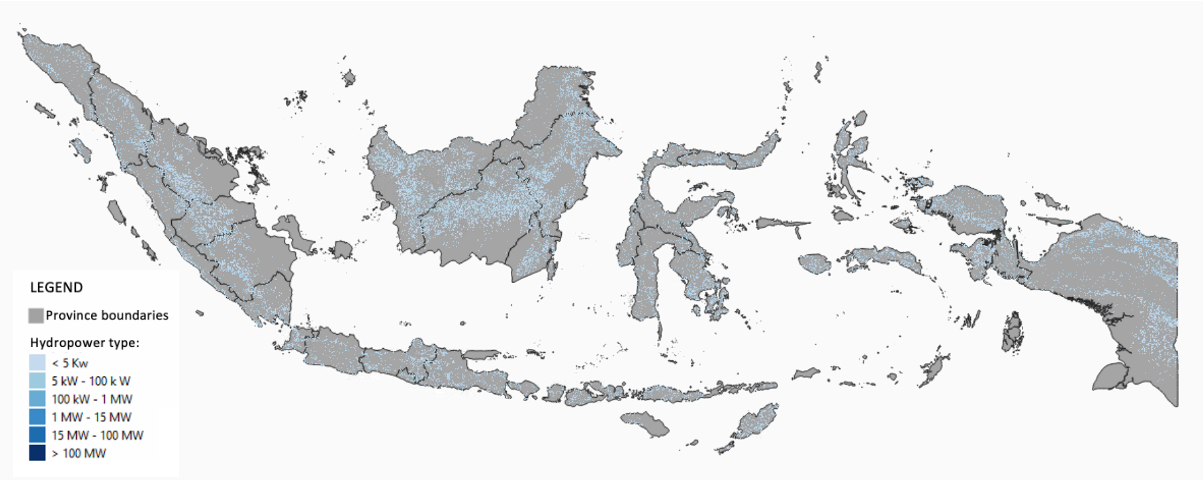


(a) Pico hydropower (< 5 kW) and micro hydropower (5 kW – 100 kW)

(b) mini hydropower (100 kW – 1 MW) and small hydropower (1 MW – 15 MW)

(c) medium hydropower (15 MW – 100 MW) and large hydropower (> 100 MW)

Figure 8 Spatial distribution of hydropower potential using USGS DEM



(a) Pico hydropower (< 5 kW) and micro hydropower (5 kW – 100 kW)

(b) mini hydropower (100 kW – 1 MW) and small hydropower (1 MW – 15 MW)

(c) medium hydropower (15 MW – 100 MW) and large hydropower (> 100 MW)

Figure 9 Spatial distribution of hydropower potential using MERIT DEM

The differences between Figure 8 and Figure 9 are not significant; however, it can be seen in Table 5 in Appendix A that the gross theoretical potential results analysis using MERIT DEM is higher than USGS DEM (further explanation in section 5.1.3). This might be due to differences of pixel size as mentioned in Section 5.1.1.

5.1.3 Indonesia's gross capacity potential

The total national theoretical potential will be obtained from 2 sources, USGS and MERIT. DEMNAS will only be used to calculate the theoretical potential of Bali, East Nusa Tenggara (NTT) and Maluku. Based on the calculated results in Table 5 in Appendix A, 1 arcsecond (USGS) DEM result in a total theoretical gross hydropower potential of 163 GW with an annual energy generation of 1400 TWh, whereas 3 arcseconds (MERIT) DEM shows a theoretical gross hydropower potential of 187 GW with an annual energy generation of 1600 TWh. Figure 13 shows that the three largest contributors to total theoretical hydropower potential are Papua, Kalimantan and Sumatra. The distribution of theoretical hydropower potential on each island is depicted in Figure 13 and Figure 12 contains information on the distribution of potential between the different sources; large, medium, small, mini, micro and pico hydropower.

In general, large hydropower locations account for about 5% of the total capacity potential, medium hydropower accounts for around 17%, small hydropower accounts for around 40%, mini hydropower accounts for 26% to 29%, micro hydropower accounts for around 5% to 11% and pico hydropower accounts for around 0.02% to 0.07%. The amount of large and medium hydropower is much less common and unequally spread compared to pico and micro, however the total amount of capacity of both large and medium could cover around 70% of mini hydroelectricity power capacity. According to Figure 13, Kalimantan and Papua theoretically have a large number of potential sites for medium and large hydropower, as shown in Table 6 and 7, which also indicates that the number of medium and large sites in these two islands are greater than on the other islands. This study concludes that the contribution of large hydropower increases in larger areas, and in smaller catchments or islands, micro, mini and small hydropower play a larger role. It stands to reason that this would be the case given the prevalence of large river formations in larger areas. A further factor, particularly for Indonesia, could be that larger islands like as Kalimantan, Papua, and Sumatra are appropriate for large hydropower because those islands have ample space, unlike Java, which has a high population density.

Comparing the results of USGS, MERIT and DEMNAS, it is found from the results that DEMNAS with 0.27 arcseconds detects far more pico hydropower potential than the other two sources. Since the pixel size of DEMNAS is approximately four times smaller than USGS and eleven times smaller than MERIT, this DEM performs better when computing the smaller scale of hydropower potential. However, different case occurs for medium to large-scale hydropower, that MERIT could result in better estimation since the pixel size is larger. In Table 5, the only DEM source that could detect medium hydropower potential in Bali is MERIT, meanwhile based on USGS and DEMNAS the potential for medium hydropower is absent. Nevertheless, it is important to note that for small islands using MERIT DEM could be prone to underestimated or overestimated results due to the pixel size. This is concluded by comparing the results of MERIT and the other two sources, specifically in small hydropower in all islands. The MERIT results of small hydropower potential in small islands (i.e. NTT, Bali, Maluku and North Maluku) are smaller compared to USGS and DEMNAS, but in larger island, like Kalimantan, Sumatra, Papua, Java and Sulawesi, the calculate theoretical potential is higher than the results of USGS and DEMNAS.

Figure 10 Theoretical potential result (USGS)

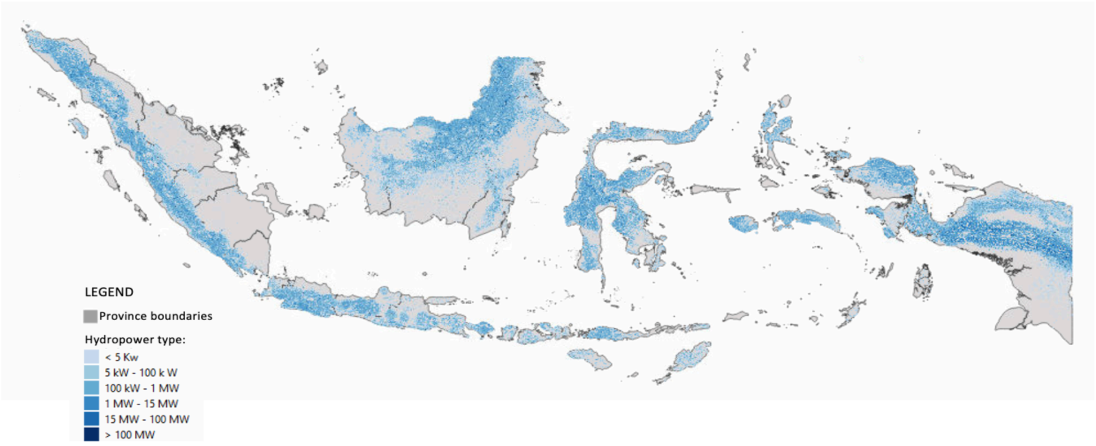


Figure 11 Theoretical potential result (MERIT)

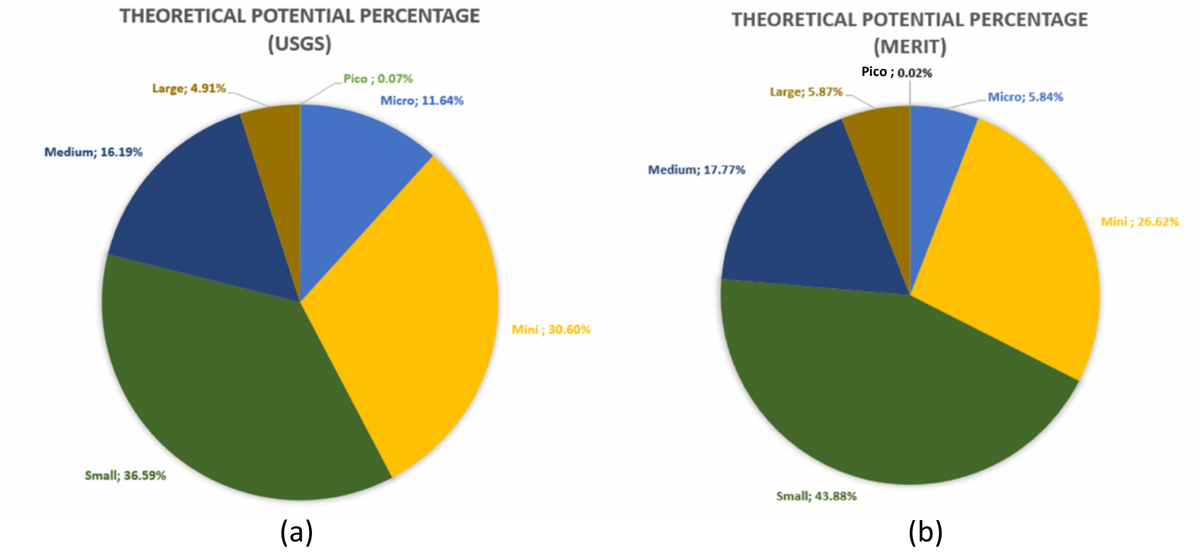
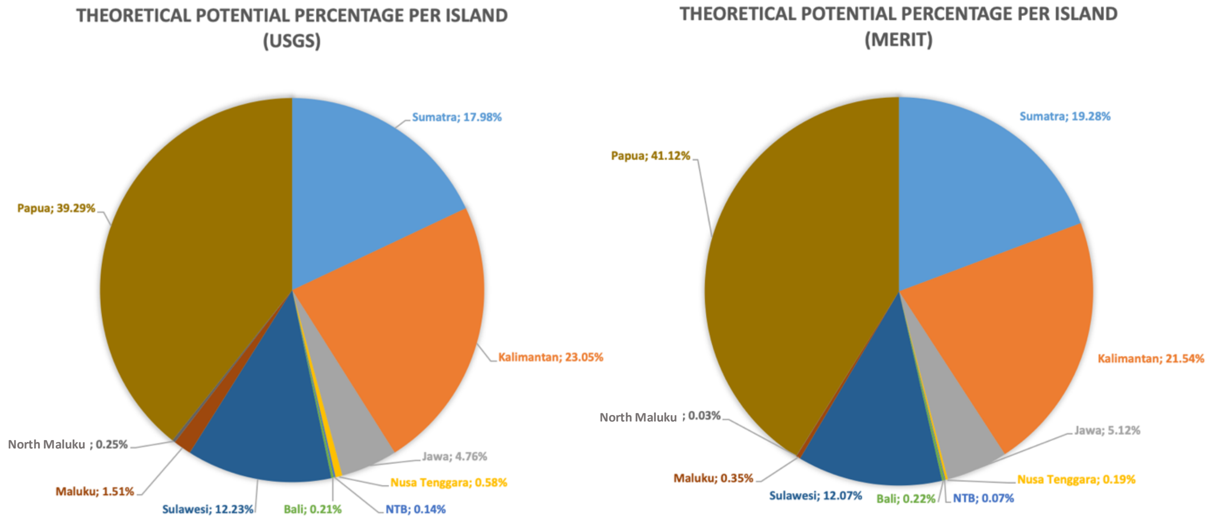


Figure 12 Theoretical potential distribution percentage of all hydropower types using DEM from (a) USGS and (b) MERIT



(a) (b)

Figure 13 Theoretical potential distribution percentage per island using DEM from (a) USGS and (b) MERIT

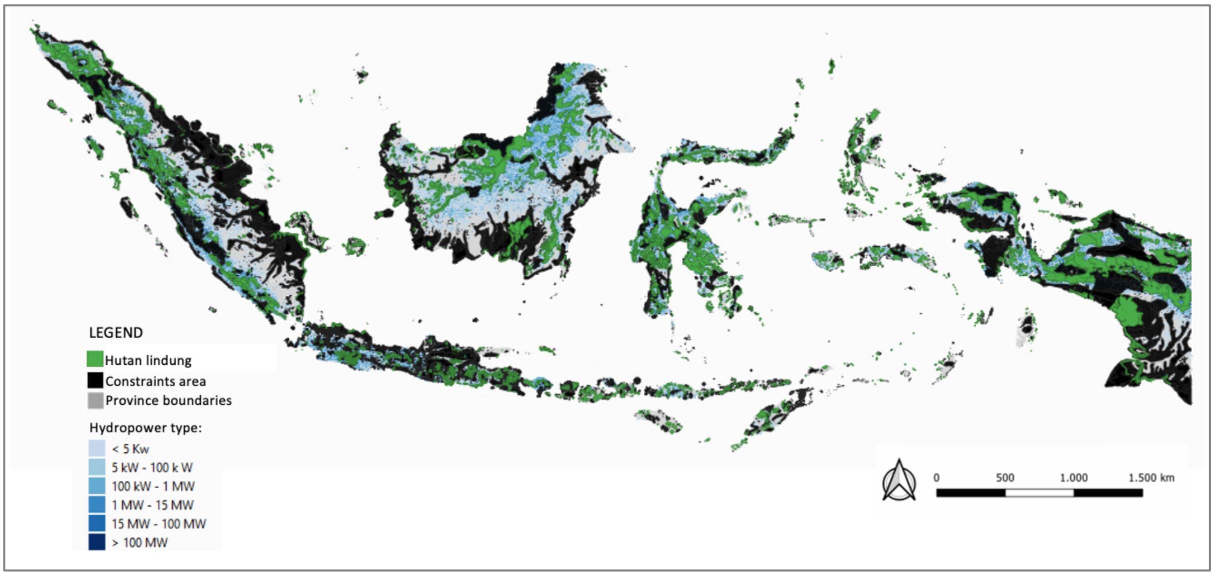
5.2 Technical potential of hydropower

Several technical constraints (hydrological, topographical and geological condition) and non-technical constraints (land use and natural disaster-prone zone) are also decreasing the amount of calculated theoretical potential. For the technical constraints, as mentioned in section 3.3.2, the hydrological and topographical condition was already filtered during the theoretical potential analysis step when delineating the river discharge from runoff data. As for geological condition several classifications of soil—vertisols, gleysols, fluvisols, histosols—were added to the constraint criteria by retrieving a soil classification map from the FAO GeoNetwork. The selected soil classification is characterised with soft, expansive, and low-strength soil that is predominantly composed of clay and sand. For the non-technical aspects, certain land use such as residential, industrial, military, recreational area, private land use and cemetery. Meanwhile, for natural disaster aspects, geological natural disasters such as tsunami, earthquake, landslide, volcano were included. According to Nicolas et al. and the World Bank (2019), It is crucial to include natural disasters in hydropower planning and site selection in order to prevent physical damage and service disruptions. There are three main incidents that can lead to system breakdowns, e.g. transmission and distribution grid failure, and fuel and maintenance supply chain failures (Schweiker et al., 2019).

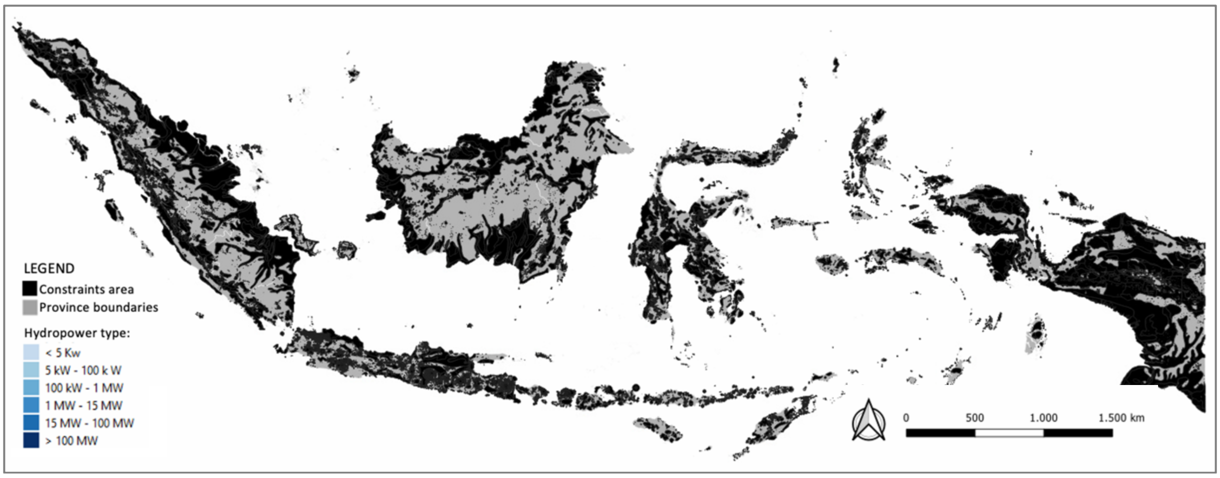
The technical potential decreased to more than half of the theoretical potential due to several constraints added to eliminate desirable suitable locations for hydropower plants. The maps of the constraint areas can be seen in Figure 14, Figure 14a shows the constraints area map without including the protected forest while Figure 14b shows if the protected forest is included in the criteria. Protected forest—which has the main function as the protection of natural resource systems to regulate the air system, prevent flooding, control erosion, prevent sea air intrusion, and maintain soil fertility—plays an important role in the preservation of nature. Since large storage hydropower could cause inundation and flooding, installing hydropower in protected forest will harm the ecosystem and the area around.

However, it will be separated from the constraints criteria (see Figure 14a) since it is still possible to install pico, micro and mini hydropower with permit from government or IPPKH (borrow-to-use forestry permit), although it is not recommended to install large hydropower plant.

Compared to the theoretical potential portion, the technical capacity potential results in a lesser amount of hydropower capacity and energy generation due to the reduction factor from the turbine efficiency (η) of 70%, as mentioned in methodology Section 4.3.1. According to International Hydropower Association (2016), the technical potential of hydropower in Indonesia is 75 GW or equal to 657 TWh of annual energy generated. The difference between the calculated potential with another study could be due to the different percentages of efficiency (η and CF) used in the calculation. Another factor is the use of differing DEM sources in the research, as it can be seen from the results in Table 8 and 9, the calculated total potential of hydropower capacity and annual energy generated using three different resolutions resulting in various ranges of output. Major influence comes from the head and the discharge as seen in Equation 2, and since there are some distinctions in discharge simulation between these two sources (see Section 4.1.1), it is then possible to have various results. As for the calculated potential, higher potential capacity from MERIT Dem has expected since, in theoretical potential, the results are also high. Small and mini hydropower are still predominantly contributing to the total potential (see Figure 17).



(a)



(b)

Figure 14 (a) Maps of protected forest and constraint areas. (b) Maps of protected constraint areas including the protected forest.

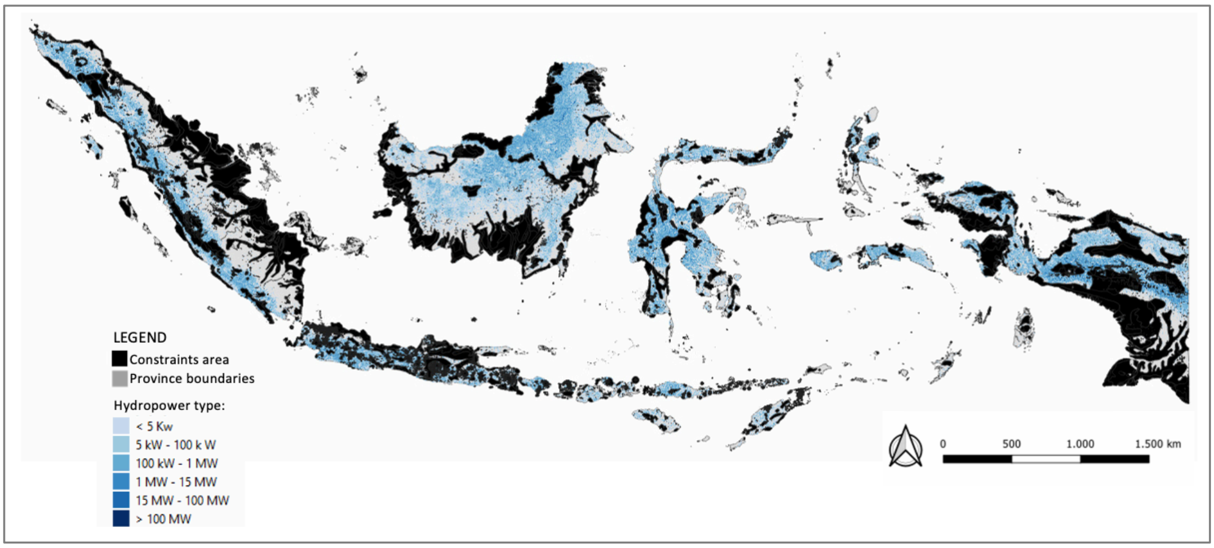


Figure 15 Technical potential result (USGS)

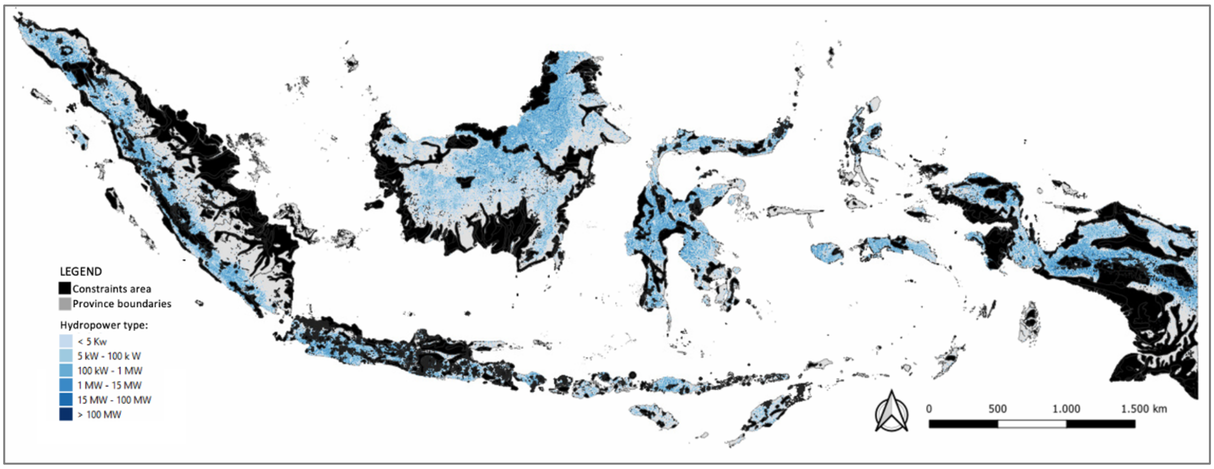
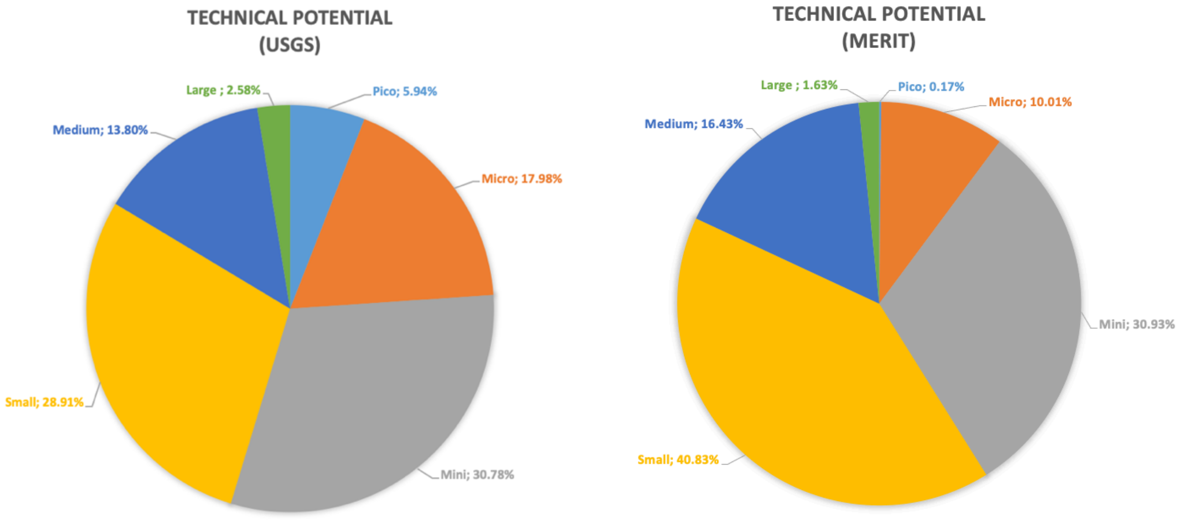
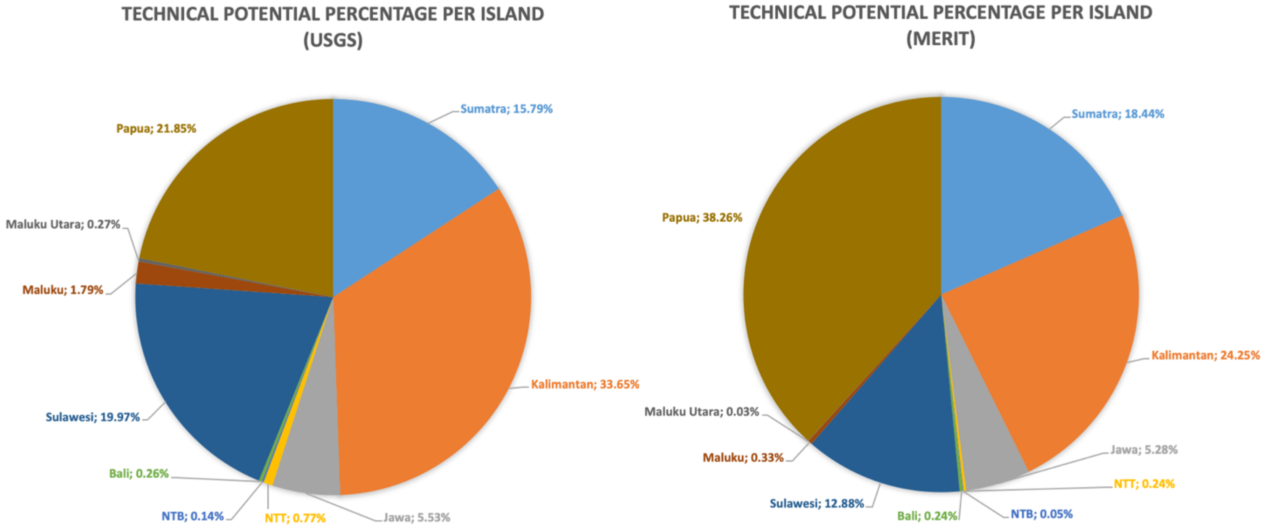


Figure 16 Technical potential result (MERIT)



(a) (b)

Figure 17 Technical potential distribution percentage of all hydropower types using DEM from (a) USGS and (b) MERIT



(a) (b)

Figure 18 Technical potential distribution percentage per island using DEM from (a) USGS and (b) MERIT

5.3 Economic potential of hydropower

After executing the technical potential, the economic potential analysis is conducted by calculating the LCOE and eliminating the location with LCOE higher than the highest range of the BPP in every island, as explained previously in Section 4.4.2. Every location with LCOE higher than the maximum BPP in that location will be taken out from the consideration. The results of economic potential and LCOE will be divided based on scenario A and scenario B. In scenario A, which is the more profitable scenario, the national economic potential from 1 arcsecond DEM is 56 GW with annual energy production of 490 TWh, and from arcseconds DEM the national economic potential is 78 GW with annual energy production of 690 TWh. Meanwhile, in scenario B, the total economic potential is 27 GW (1 arcsecond DEM) and 36

GW (3 arcseconds DEM), while the annual energy production is 240 TWh and 319 TWh from 1 arcsecond DEM and 3 arcsecond DEM, respectively.

The calculated LCOE can be seen in Table 9 in Appendix C. Based on the calculation, the higher hydropower capacity resulting in more economical LCOE because the annual energy production will also increase. In order to give a better understanding, Table 3 and 4 present the comparison between highest and lowest LCOE in Bali Island based scenario A and B.

Table 3 Comparison between scenario A and scenario B of lowest LCOE in Bali

	Scenario A			Scenario B		
	DEMNAS	USGS	MERIT	DEMNAS	USGS	MERIT
Hydropower capacity [MW]	9	6	12	3	3.5	7
Head [m]	319	309	582	319	309	582
Capacity Factor	0.86	0.86	0.86	0.5	0.5	0.5
Annual energy production [GWh/year]	52	53	103	30	31	60
CAPEX [million USD]	7.3	7.6	12	13	13	20
OPEX [million USD]	0.2	0.2	0.3	0.3	0.4	0.6
LCOE [US ¢/kWh]	1.9	1.9	1.5	5.8	5.7	4.6

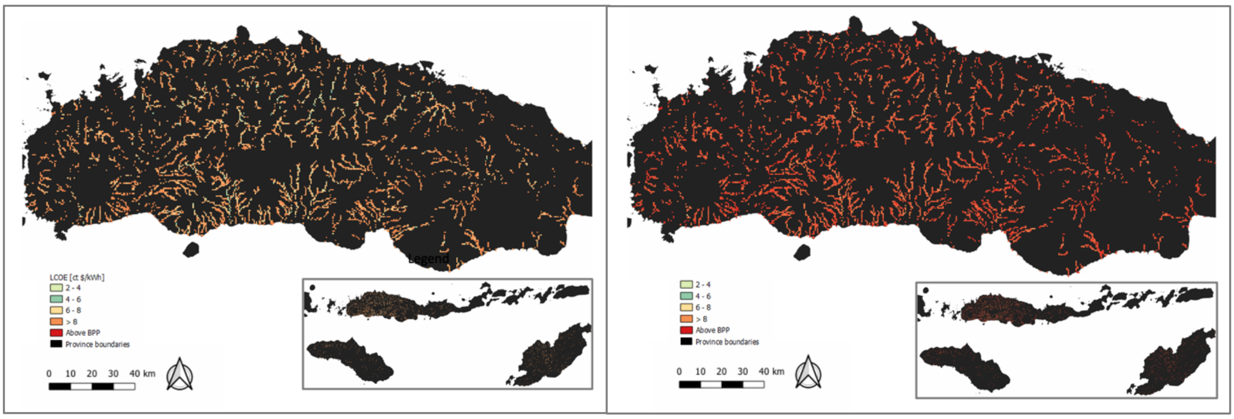
Table 4 Comparison between scenario A and scenario B of highest LCOE in Bali

	Scenario A			Scenario B		
	DEMNAS	USGS	MERIT	DEMNAS	USGS	MERIT
Hydropower capacity [MW]	0.004	0.004	0.004	0.004	0.004	0.004
Head [m]	4	4	4	4	4	4
Capacity Factor	0.86	0.86	0.86	0.5	0.5	0.5
Annual energy production [GWh/year]	0.04	0.04	0.04	0.04	0.04	0.04
CAPEX [million USD]	0.04	0.04	0.004	0.1	0.1	0.1
OPEX [million USD]	0.001	0.001	0.001	0.004	0.004	0.004
LCOE [US ¢/kWh]	17	17	17	45	45	45

From the table, it can be concluded that building low-capacity hydropower could be more costly compared to the larger one. Further explanation regarding the impact of input parameters on the calculated LCOE will be discussed in Section 5.4. The LCOE variety for the best scenario ranges from 0.01 US ¢/kWh to 0.2 US ¢/kWh, according to Table 9. On the other hand, LCOE in the worst scenario goes from 0.02 to 0.6 US ¢/kWh based on the results of DEMNAS, USGS and MERIT. The maps of the economic hydropower potential from all three sources can be seen in Figure 19, 20, 21 and 23.

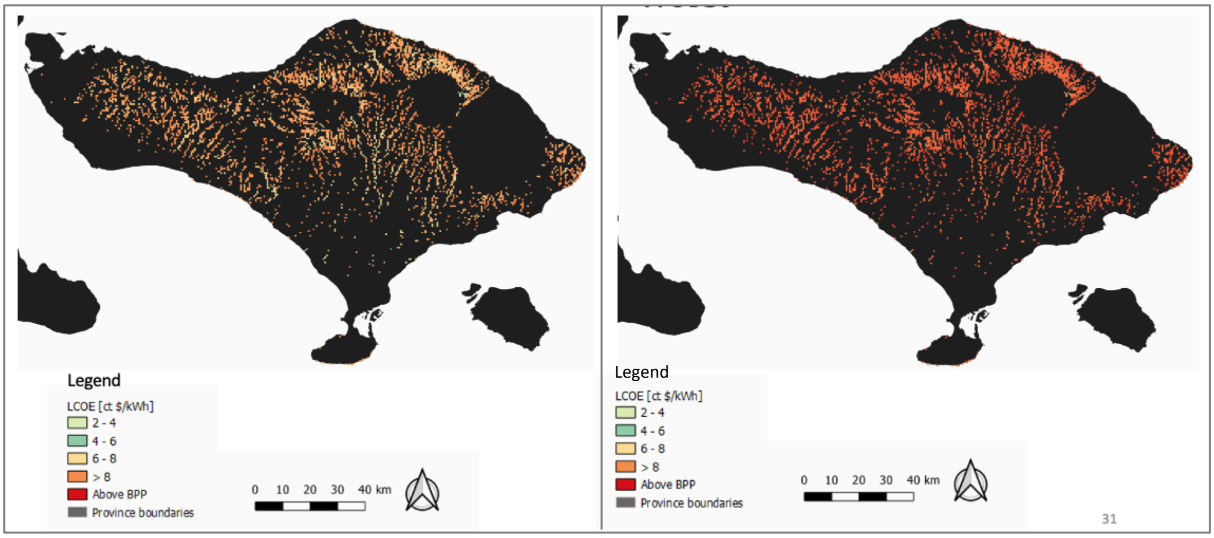
On theoretical and technological potential analyses, the DEM resolution appears to have a significant impact on the outcomes, both the location and the calculated hydropower capacity. In the LCOE calculation, MERIT as the biggest pixel size DEM provides the smallest

LCOE compared to the other two sources. In order to explain the reason, lowest LCOE range in scenario A (Table 3) will be used as an example. When calculating the CAPEX using equation 4 using DEM from USGS, the head (309 m) is reduced to 0.47 whilst the capacity (6 MW) is reduced to 7.39. While using MERIT DEM, the head (582 m) is reduced to 0.43 and the capacity (13 MW) is reduced to 6.94. On the other hand, the energy generated estimated from MERIT DEM remains higher (103 GWh) compared USGS DEM (53 GWh). In other words, higher value of head and capacity could reduce the capital expenditure while still generating higher amount of energy, and so the LCOE will be lower.



(a) (b)

Figure 19 (a) Best scenario of economic potential in East Nusa Tenggara using DEMNAS DEM, (b) Worst scenario of economic potential in East Nusa Tenggara using DEMNAS DEM



(a) (b)

Figure 20 (a) Best scenario of economic potential in Bali using DEMNAS DEM, (b) Worst scenario of economic potential in Bali using DEMNAS DEM

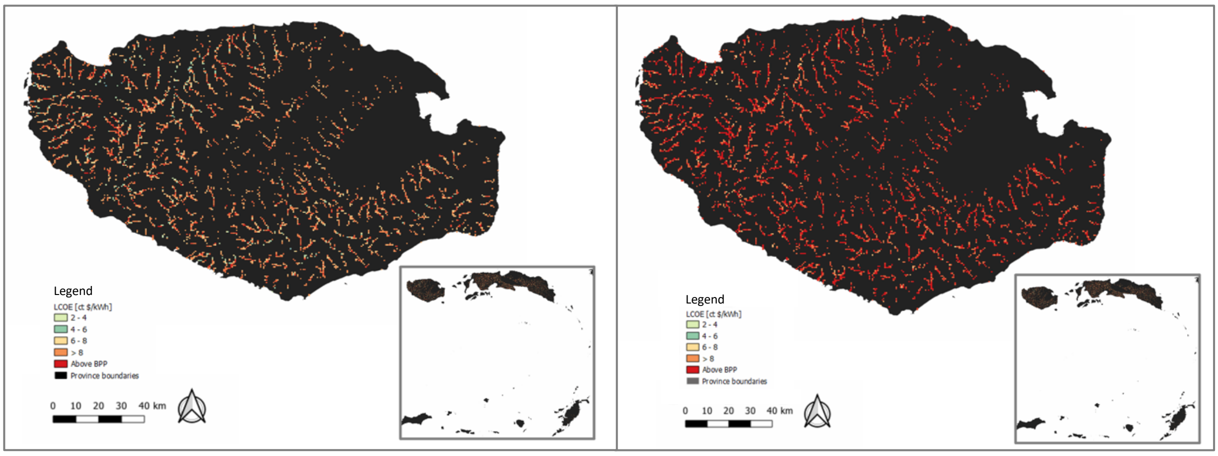


Figure 21 (a) Best scenario of economic potential in Maluku using DEMNAS DEM, (b) Worst scenario of economic potential in Maluku using DEMNAS DEM

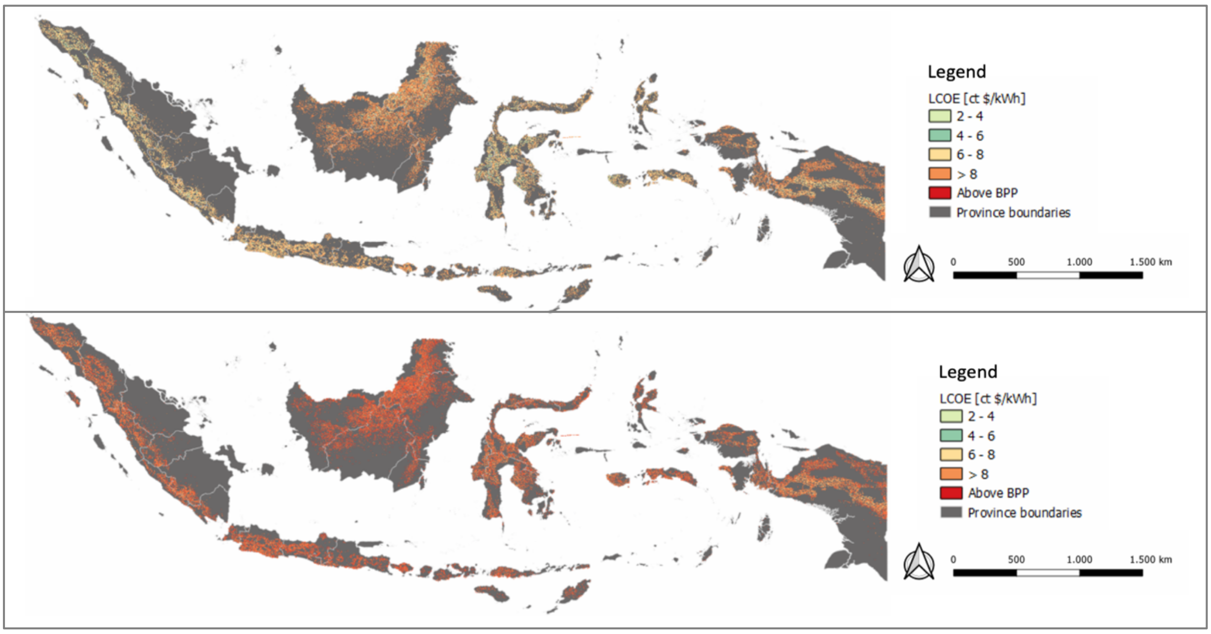


Figure 22 Best scenario (above) and Worst scenario (below) of economic potential of hydropower in Indonesia using USGS DEM

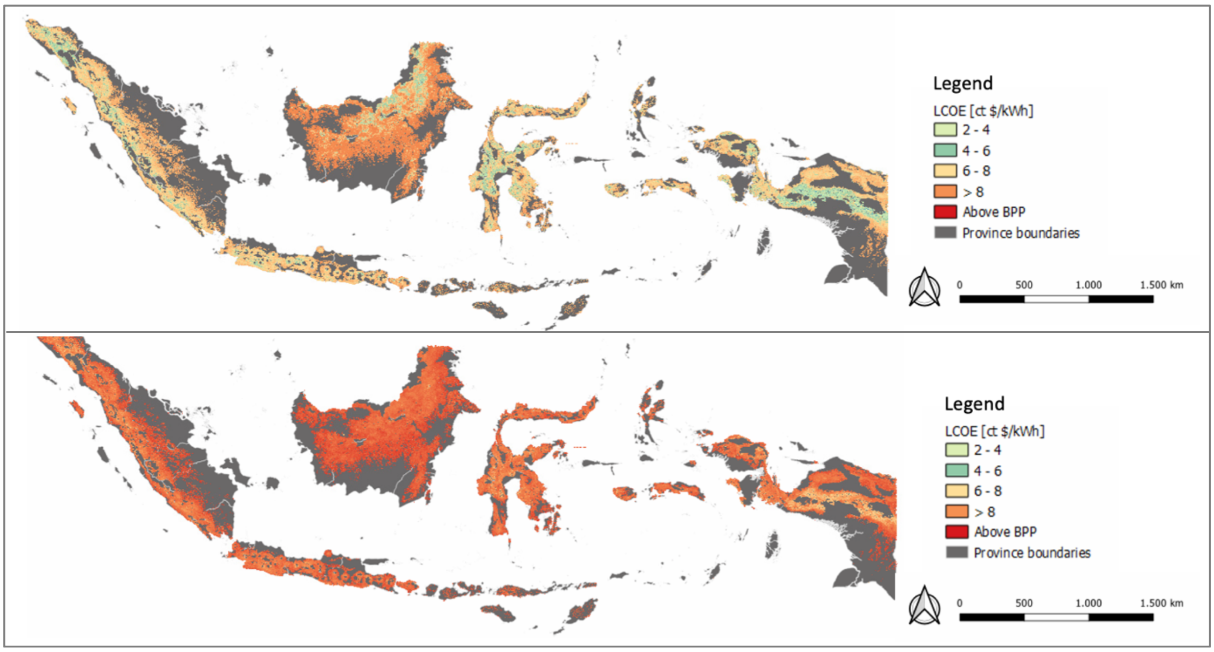


Figure 23 Best scenario (above) and Worst scenario (below) of economic potential of hydropower in Indonesia using MERIT DEM

5.4 Sensitivity analysis

The input parameters of LCOE are varied in this analysis to understand the sensitivity of the LCOE towards the inputs. The parameters will be increased and decreased by 20%, and the result can be seen in Figure 24. The figure indicates the LCOE is very sensitive to changes in CAPEX. According to (Tran & Smith, 2018), capital costs are also a significant factor in total project costs and are crucial for measuring LCOE. Hence, the sensitivity is higher compared to the other parameters. Like CAPEX, discount rate also gives a high sensitivity impact, as based on equation 6, the discount rate is included in the calculation of CRF (see equation 7) that further has a direct impact to the capital cost in calculating the LCOE. OPEX, on the other hand, has a low impact towards the LCOE as operation and maintenance costs of renewable energy technologies are oftentimes much lower than the capital cost due to the low maintenance required (Tran & Smith, 2018). Tefera and Kasiviswanathan (2022) also mention in their study that WACC influences the magnitude of LCOE. As for the hydropower capacity, the influence on the LCOE is modest, since in the CAPEX calculation, the capacity will be reduced to the power of 0.78. However, raising the hydropower capacity to 20% will impact on an increase of the CAPEX by 15%. The other parameters, head and lifetime, also give insignificant impact on LCOE.

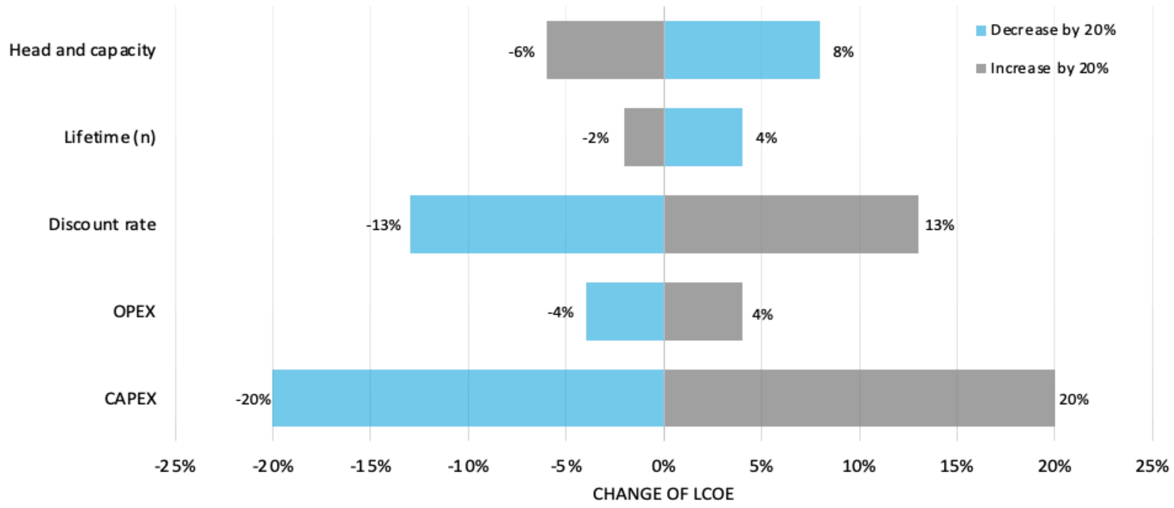
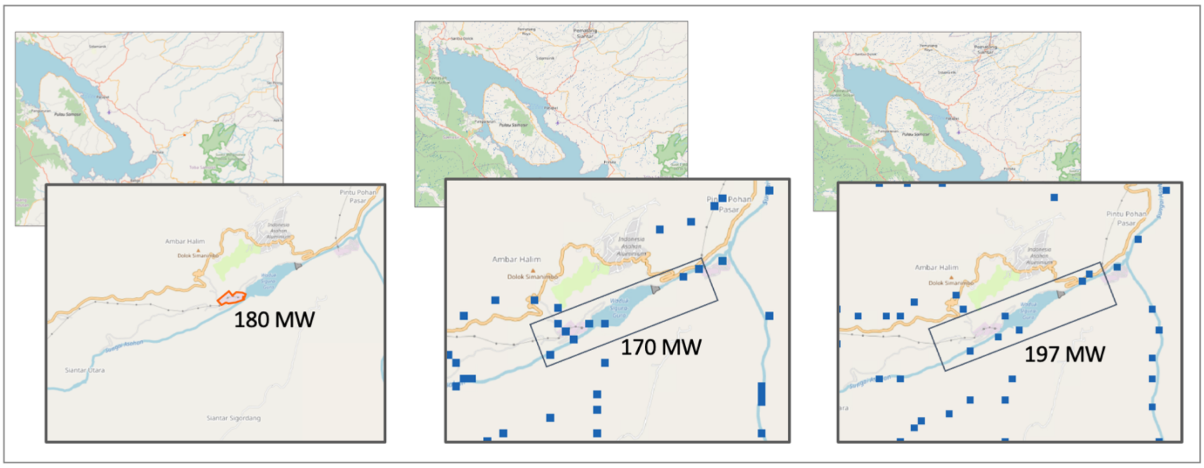


Figure 24 Sensitivity of the LCOE to its input variables

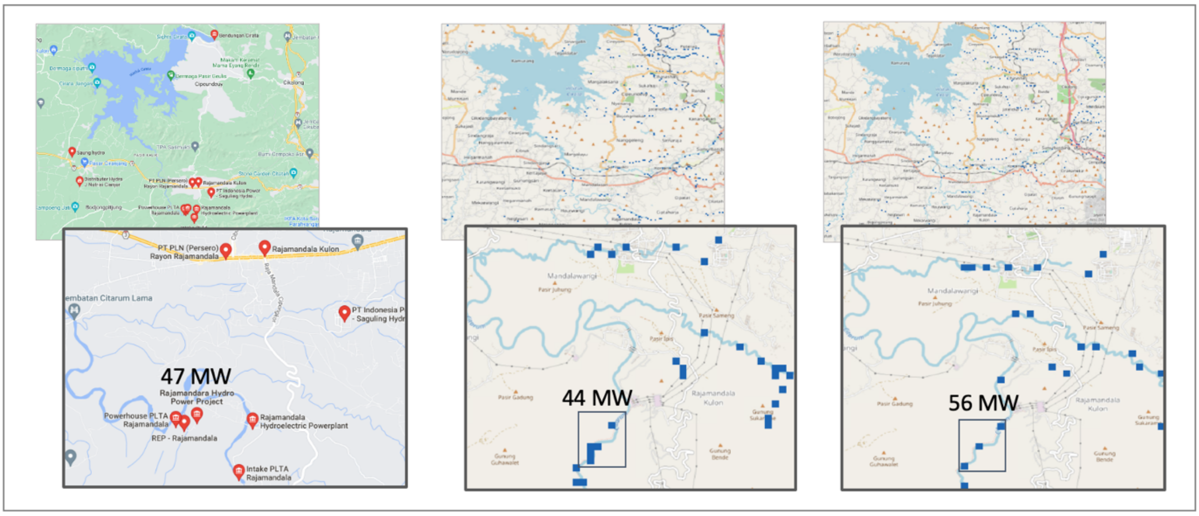
5.5 Validation of the results

The results from technical potential will be validated by comparing it with the real location of HPP and the planned location for HPP. Figure 25 shows the location of Asahan HPP in North Sumatra in comparison with the obtained simulation results of the area near Asahan HPP and Figure 26 at Rajamandala HPP in West Java. It can be seen in the Figure 25 the simulation using USGS DEM shows that the sum hydropower potential around the Asahan HPP is 170 MW, whilst MERIT DEM shows that the total potential around the HPP is 197 MW. Hydropower potential is also found near the Rajamandala HPP (see Figure 26), with the estimated total potential of around 44 MW to 56 MW, based on USGS DEM and MERIT DEM respectively. Different than Asahan and Rajamandala, Kayan HPP has not been constructed but the plan is to install the HPP in 5 different location which can be seen in Figure 27. The total capacity planned to be install in those locations is 17 GW. It is found from the simulation that around the project location, there is approximately 19 GW to 28 GW hydropower potential.



(a) (b) (c)

Figure 25 (a) location and the capacity of Asahan Hydropower, North Sumatra. (b) Simulation result of USGS. (c) Simulation result of MERIT.



(a) (b) (c)

Figure 26 Figure 19 (a) location and the capacity of Rajamandala Hydropower, West Java. (b) Simulation result of USGS. (c) Simulation result of MERIT.

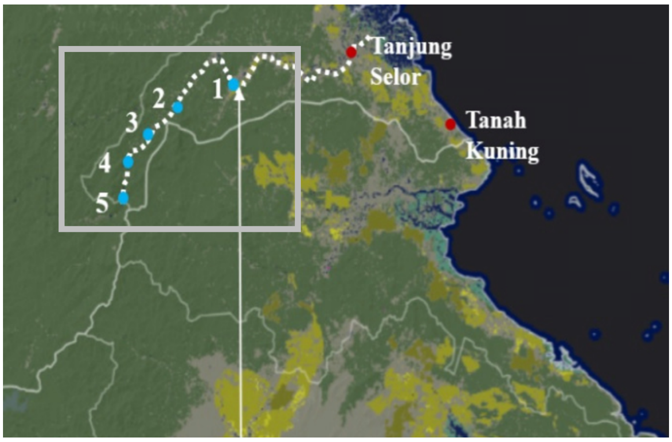
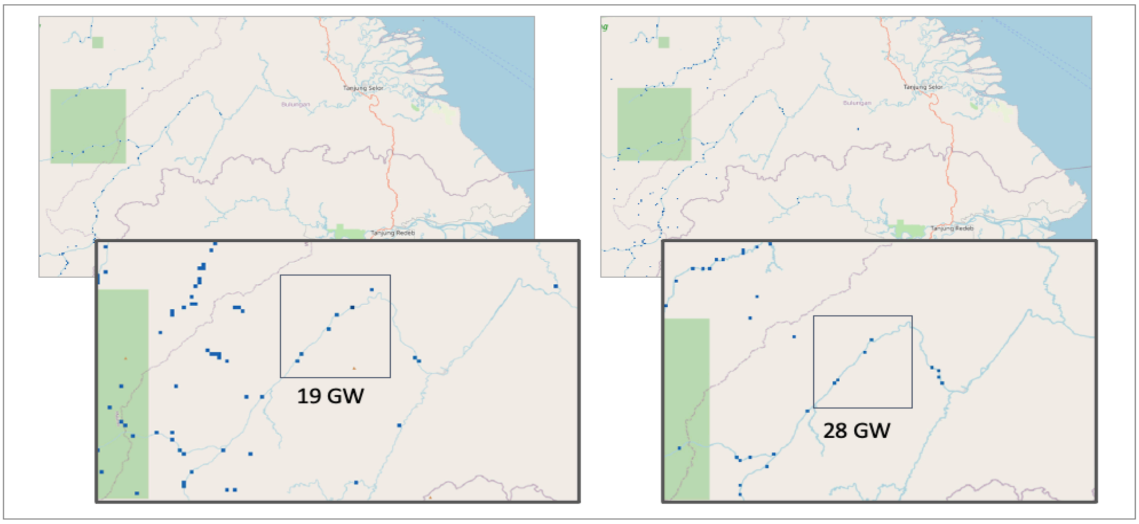


Figure 27 Kayan Hydropower project location plan (The Borneo Post, 2022).



(a) (b)

Figure 28 (a) Simulation result of USGS. (b) Simulation result of MERIT.

The resolution of DEM used could affect the result of the hydropower potential in certain area as discussed in Section 5.1. The estimated hydropower potential in this study could be lower or higher than the actual hydropower plant. The actual installed capacity could be higher than the rated capacity, and in reality, the rated capacity could be lower than the installed capacity due to several factors, such as the seasonal change of river discharge and turbine efficiency in every location. Moreover, MERIT DEM tends to result in higher estimation due to the size of the pixel. Coarser resolution of DEM is prone to overestimate or underestimate due to the limitation of the detail spatial map.

Table 5 shows the comparison between the obtained results of technical potential and the statistical data from EBTKE (2015) (Directorate General of New and Renewable Energy and Energy Conservation).

Table 5 Comparison of hydropower potential

	Estimates technical potential in this research [GW]			Estimated potential from other sources [GW]
	DEMNAS	USGS	MERIT	Statistic report from EBTKE
Kalimantan		21	19	29.7
Sumatra		10	15	21.3
Java		4	4	7.1
Sulawesi		13	10	11.8
Papua		14	31	22.9
Bali	0.2	0.2	0.2	0.76
NTT	0.6	0.5	0.2	
NTB		0.1	0.04	
Maluku	2	1	0.3	0.21
North Maluku		0.2	0.02	

To attain carbon neutrality and to meet future electricity demand, PLN requires additional 413 Gigawatts (equal to 3617 TWh) of installed electricity capacity (GW) in which a large portion of the mix will come from renewable energy, which is 308 GW (annual energy production of 2690 TWh). Since the total economic potential is ranging from 64 GW—80 GW and the annual energy ranges from 240 TWh—690 TWh, hydropower could actually cover 9% to 25% of the total required additional capacity. According to IEA, the electricity consumption in 2019 in Indonesia accounts for 271.7 TWh. Comparing to the calculated total economic potential, the electricity consumption is still in the range of estimation (240 to 690 TWh) and thus the hydropower could actually cover the electricity consumption.

5.6 Impact on carbon emission

Hydropower is a low-carbon form of renewable energy and a dependable, cost-effective alternative to fossil fuel-based electricity generation. IAEA (2020) shows that the substitution of hydropower for fossil fuels in the generation of electricity has prevented more than 100 billion tCO_2 emissions in the previous 50 years. According to the International Hydropower Association (IHA), global emissions from fossil fuels and industry would increase by at least 10% if hydropower were substituted by burning coal to generate energy. This amounts to more than 4 billion metric tonnes of additional greenhouse gases emitted yearly. Based on the finding from IPCC, the mean carbon emission for hydropower is accounted for 24 gCO_2 -eq/kWh or equal to 0.024 tCO2 -eq/TWh, while the carbon emission for fossil fuel based on study of Langer et al. (2022) is accounted for 1.16 tCO_2 -eq/TWh and. Figure 29 shows the comparison of emitted carbon emission of several energy sources.

The results of technical potential and economic potential will be used to determine the reduction of carbon emission, assuming all the hydropower potential is utilized. The carbon emission based on technical hydropower potential analysis, 558 TWh energy generation (USGS DEM) is resulting in approximately 13 tCO_2 -eq/TWh carbon emission, while 702 TWH (MERIT DEM) is resulting in around 17 tCO_2 -eq/TWh of carbon emission. Assuming similar number of energy generation is from fossil fuel, it could emit around 650 tCO_2/TWh (USGS DEM) and 810 tCO_2/TWh (MERIT DEM). From this estimation, the reduction of CO_2 emission accounts for around 90%. Moreover, based on economic potential, around 240—490 TWh energy generation (USGS DEM) result in approximately 6—12 tCO_2 -eq/TWh carbon emission, while range of 310—690 TWh (MERIT DEM) result in around 9—16 tCO_2 -eq/TWh of carbon emission. Meanwhile from fossil fuel, the CO_2 emission range is 278—568 tCO_2 -eq/TWh for USGS DEM and 360—800 tCO_2 -eq/TWh for USGS DEM. It can be concluded that the carbon emission could be reduced also by around 90%.

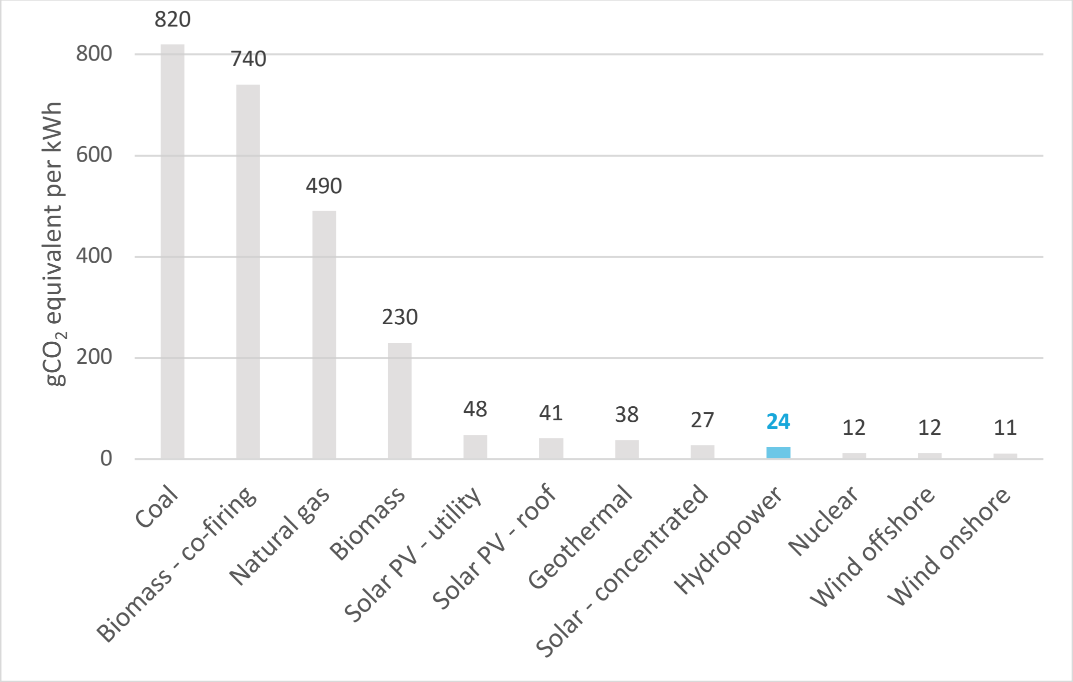


Figure 29 | Median emissions of electricity generation technologies from various sour

6 | Conclusion & Recommendation

In the chapter, the concluding answer to the research questions will be discussed in Section 6.1. Lastly, limitation of this study and recommendation for future research will be explained in last section.

6.1 Conclusion

1. ***What is the theoretical potential of hydropower in Indonesia?***

   The obtained theoretical potential of hydropower was divided based on the source of DEM used when processing data in GIS. There are three DEM sources, namely DEMNAS (0.27 arcseconds resolution), USGS (1 arcsecond resolution) and MERIT (3 arcseconds resolution). From the 1 arc second DEM, the total theoretical potential for the entire Indonesia is approximately 163 GW or equal to 1400 TWh of annual energy production, where approximately 1 TWh contributed from pico, 160 TWh from micro, 430 TWh from mini, 520 TWh from small, 230 TWh from medium and the rest is large hydropower.

   As for MERIT DEM, the total potential is higher, accounted for 187 GW with annual energy production of 1600 TWh. The highest contributions of energy production are coming from small and mini hydropower, accounting for 718 TWh and 435 TWh, respectively. Since MERIT DEM has a bigger pixel size, hence the ability to determine the location and the capacity for pico and micro is lower compared to USGS and DEMNAS, resulting 370 TWh of pico and 95 TWh of micro. However, using MERIT DEM for estimating the hydropower potential in small islands is prone to underestimated or overestimated results due to the pixel size. The results of small hydropower potential from MERIT DEM in small islands (i.e. NTT, Bali, Maluku and North Maluku) are smaller compared to USGS and DEMNAS, but in larger island, like Kalimantan, Sumatra, Papua, Java and Sulawesi, the calculate theoretical potential is higher than the results of USGS and DEMNAS.

   The theoretical potential from DEMNAS DEM will not be presented as national theoretical potential since only 3 islands (NTT, Bali and Maluku) are computed. However, from the discharge simulation result, DEMNAS could delineate the river shape more accurately eveb in flatter area near the estuary. This DEM also performs better when computing the smaller scale of hydropower potential since the pixel size of DEMNAS is approximately four times smaller than USGS and eleven times smaller than MERIT.

   In conclusion, the total theoretical potential of hydropower in Indonesia is ranging from around 162—187 GW with annual energy generation ranges from 1400—1600 TWh depending on the several assumptions used in the calculation and the DEM resolution.

2. ***What is the technical potential of hydropower in Indonesia?***
   After calculating the gross potential in the previous step, the analysis continued with an evaluation of the technical potential. The results from theoretical potential is used as the initial input for the technical potential, and later on, was continued by adding several constraint criteria which is already mentioned on Chapter 4 and 5. The total technical potential of hydropower decreases by around 60 % from the theoretical calculation ranges between 64 GW to 80 GW and the annual energy production accounts for around 550 TWh to 700 TWh as can be seen in Table 8 and 9. The results of the analysis show that the highest potential lies in Papua and Kalimantan, followed by Sumatra and Sulawesi. As for the hydropower type, the highest contribution came from mini and small hydropower with total potential of 750 TWh (USGS) and 1100 TWh (MERIT).

3. ***What is the economic potential of hydropower in Indonesia?***
   The economic potential for this study is determined based on LCOE and BPP. As discussed in Section 4.4.3. There are two scenarios in calculating the LCOE, namely scenario A (more profitable scenario) and scenario B (lest profitable), where LCOE in scenario A ranges from 1—19 US ¢/kWh and in scenario B ranges from 2—59 ¢/kWh. After the selection of economically feasible LCOE, the economic potential is then quantified. From USGS DEM, the potential is ranging between 27 GW to 56 GW with annual energy production ranges from 240 to 490 TWh. Higher results come out from MERIT DEM where the hydropower potential approximation is between 35 to 79 GW with estimated annual energy production accounts for around 310 to 690 TWh. Meanwhile for DEMNAS DEM, since there are only three islands (Bali, East Nusa Tenggara and Maluku) included in the calculation, thus the total national energy potential could not be calculated. The economic potential for Bali is around 0.06 GW 0.1 GW, while in East Nusa Tenggara is around 0.03 to 0.3 GW and Maluku is around 0.2 to 0.8 GW.

   The effect of DEM resolution lies in the results of calculated LCOE. The higher value of head and capacity could reduce the capital expenditure while still generating a higher amount of energy, resulting in a lower value of levelized cost of electricity. Since MERIT DEM has the largest pixel size compared to USGS and DEMNAS, the calculation of LCOE using DEM from MERIT resulted in cheaper LCOE.

4. ***How much could CO_2 emissions be reduced from hydropower utilisation?***
   Based on the finding from IPCC, the mean carbon emission for hydropower is accounted for 24 gCO_2 -eq/kWh or equal to 24 tCO2 -eq/GWh, while the carbon emission for fossil fuel based on study of Langer et al. (2022) is accounted for 1158 tCO_2 -eq/GWh. From the technical potential, it is estimated that if all the potential is implemented, hydropower plant will emit 13—17 tCO2 -eq/TWh from producing around 558—702 TWh of annual energy. While in from fossil fuel generation, it could emit around 650—810 tCO_2 -eq/TWh.

   From the economic potential perspective, around 240—490 TWh energy generation (USGS DEM) result in approximately 6—12 tCO2 -eq/TWh carbon emission, while for annual energy generation of 310—690 TWh (MERIT DEM), the emission is around 9—16 tCO_2eq/TWh of carbon emission. Meanwhile from fossil fuel, the CO_2 emission range is 278—568 tCO2 -eq/TWh for USGS DEM and 360—800 tCO2 -eq/TWh for MERIT DEM. From the analysis, It can be concluded that the carbon emission could be reduced by around 90% with the assumption that all hydropower potential is implemented.

5. ***What is the hydropower potential throughout Indonesia and the contribution of its utilisation?***
   The gross national theoretical potential of hydropower in Indonesia is around 1400 to 1600 TWh where approximately in average 22% of it is contributed from Kalimantan, 18% from Sumatra, 12% from Sulawesi and 40% from Papua. After the evaluation using the constraints criteria, the technical potential is found to be around 550 to 700 TWh, where in approximation, Kalimantan contributes for 28%, Sumatra for 17%, 16% from Sulawesi and 30% from Papua. Finally, the economic potential found in this study is about 240 to 690 TWh.

   Additional installed capacity that is required by PLN to be carbon neutral is 308 GW (2690 TWh) from renewable energy. Since the total economic potential is ranging from 240 to 690 TWh, hydropower could actually cover 9% to 25% of the total required additional capacity. According to IEA, the electricity consumption in 2019 in Indonesia accounts for 271.7 TWh. Comparing to the calculated total economic potential, the electricity consumption is still in the range of estimation (240 to 690 TWh) and thus the hydropower could actually cover the electricity consumption.

6.2 Limitation of study and future research recommendation

This study mainly used DEM of 90 m x 90 m (3 arcseconds) and 30 m x 30 m (1 arcsecond) to estimate the national hydropower potential. Higher resolution of DEM (0.27 arcsecond) is also used, but only to generate hydropower potential calculation for some of small island in Indonesia (i.e. Bali, NTT, Maluku). Since DEMNAS has very fine pixels DEM, the size of the data is very large, especially for huge islands like Kalimantan, Papua, Sumatra, Sulawesi and Java. It is suggested to have sufficient computation power and storage in order to process the whole data of Indonesia when using high resolution DEM.

There is an additional limitation when estimating the river discharge. Since this study neglected the seasonal variation of river discharge, the hydropower potential, in reality, could be different depending on the season. Additionally, several assumptions are used in this research, such as the turbine efficiency, capacity factor and cost components coefficients. Hence, the results of this study could not replace site selection and evaluations based on on-site surveys. Nevertheless, government, researchers or any other relevant parties can use this study as a reference for identifying potential hydropower locations and capacity.

In the economic potential analysis, several assumptions are used when determining OPEX, cost coefficient in CAPEX and the capacity factor. Assumptions in cost calculation are made as there is limited data of the installation and maintenance cost of hydropower in Indonesia, especially in CAPEX calculation, since the cost of hydropower installation is unique and could be different in every location depending on the head and power, type of hydropower (e.g. RoR, storage or Pumped storage hydropower) distance to the available electricity grid, condition of location and accessibility of the location. Hence, the result of this analysis could be used as benchmark, but important to note that the results are only estimation based on assumptions and modelling. This study only conducts economic potential analysis by comparing the LCOE and the range of BPP of each island. Going deeper in the economic potential is suggested for future research, such as comparing the LCOE with the actual local tariff or BPP at the nearest distance to the estimated location of the hydropower potential in order to determine the potential more accurately.

From the results of this study, it is found that hydropower could contribute around 9% to 25% to the required additional installed capacity from renewable energy, only if all locations found in this research is implemented. However, in reality, installing hydropower at all approximate sites is impossible as it might bring downside to the downstream area. It is suggested that the government look for alternative renewable energy sources to meet the additional 308 GW installed capacity plan.

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Appendix

A. Theoretical potential results

Table 6 Theoretical potential results

USGS

Hydropower capacity	Sumatra	Kalimantan	Jawa	NTT	NTB	Bali	Sulawesi	Maluku	Maluku Utara	Papua	Total per plant
Pico (GW)	0.02	0.04	0.02	0.003	0.002	0.001	0.01	0.003	0.001	0.02	0.1
Micro (GW)	4	5	2	0.3	0.1	0.2	3	0.5	0.2	3	19
Mini (GW)	11	11	3	0.5	0.1	0.1	7	1.1	0.2	17	50
Small (GW)	11	10	2	0.1	0.01	0.03	7	0.8	0.05	29	60
Medium (GW)	3	9	0.4	0	0	0	3	0.1	0	11	26
Large (GW)	0.6	3	0.2	0	0	0	0.4	0	0	4	8
Total per island (GW)	293	38	8	1	0.2	0.3	20	2	0.4	64	163

MERIT

Hydropower capacity	Sumatra	Kalimantan	Jawa	NTT	NTB	Bali	Sulawesi	Maluku	Maluku Utara	Papua	Total per plant
Pico (GW)	0.01	0.01	0.01	0.001	0.0004	0.0003	0.004	0.001	0.0002	0.01	0.04
Micro (GW)	3	3	1	0.1	0.04	0.1	2	0.1	0.03	2	11
Mini (GW)	13	12	4	0.2	0.05	0.2	7	0.3	0.02	13	50
Small (GW)	17	13	3	0.06	0.04	0.1	9	0.2	0.002	39	82
Medium (GW)	3	9	1	0	0	0.02	4	0	0	17	33
Large (GW)	1	3	0.2	0	0	0	0.3	0	0	6	11
Total per island (GW)	36	40	10	0.4	0.1	0.4	23	1	0.05	77	187

DEMNAS

Hydropower capacity				NTT		Bali		Maluku			
Pico (GW)				0.01		0.02		0.8			
Micro (GW)				0.3		0.2		0.5			
Mini (GW)				0.3		0.1		0.8			
Small (GW)				0.1		0.02		0.5			
Medium (GW)				0		0		0			
Large (GW)				0		0		0			
Total per island (GW)				0.7		0.3		2.7			

Table 7 Annual energy production based on theoretical potential result

USGS

Annual energy	Sumatra	Kalimantan	Jawa	NTT	NTB	Bali	Sulawesi	Maluku	Maluku Utara	Papua	Total per plant
Pico (GWh)	200	310	160	29	14	12	120	25	12	136	1,000
Micro (GWh)	38,500	47,000	19,000	3,000	1,200	1,400	22,300	4,300	1,400	27,900	166,200
Mini (GWh)	94,500	93,000	25,500	4,000	700	1,200	61,300	9,900	1,700	145,100	437,000
Small (GWh)	95,500	89,500	17,000	1,200	90	240	60,500	6,700	390	250,400	522,700
Medium (GWh)	23,000	75,000	3,000	0	0	0	26,900	460	0	102,000	231,200
Large (GWh)	5,300	24,000	1,800	0	0	0	2,200	0	0	35,400	70,100
Total per island (GWh)	257,000	328,800	66,400	8,200	2,000	2,800	172,300	21,300	3,500	560,900	1,400,000

MERIT

Annual energy	Sumatra	Kalimantan	Jawa	NTT	NTB	Bali	Sulawesi	Maluku	Maluku Utara	Papua	Total per plant
Pico (GWh)	82	121	49	8	4	3	35	6	1	67	370
Micro (GWh)	22,000	27,800	11,800	790	310	950	13,800	1,300	250	16,300	95,600
Mini (GWh)	113,900	103,200	37,100	1,800	460	2,000	63,700	2,500	150	111,800	435,900
Small (GWh)	148,800	116,000	27,700	510	360	440	83,000	1,800	20	339,800	718,600
Medium (GWh)	25,400	75,100	5,300	0	0	170	35,000	0	0	149,900	291,000
Large (GWh)	5,400	30,300	1,800	0	0	0	2,900	0	0	55,400	96,100
Total per island (GWh)	315,582	350,000	83,700	3,100	1,100	3,500	190,000	5,600	420	673,200	1,600,000

DEMNAS

Annual energy				NTT		Bali		Maluku			
Pico (GWh)				64		158		7,200			
Micro (GWh)				2,500		1,500		4,500			
Mini (GWh)				2,500		1,000		7,100			
Small (GWh)				560		200		4,600			
Medium (GWh)				0		0		0			
Large (GWh)				0		0		0			
Total per island (GWh)				5,600		2,800		23,400			

B. Technical potential results

Table 8 Technical potential results

USGS											
Hydropower capacity	Sumatra	Kalimantan	Jawa	NTT	NTB	Bali	Sulawesi	Maluku	Maluku Utara	Papua	Total per plant
Pico (GW)	0.04	0.07	0.04	0.01	0.003	0.003	4	0.008	0.003	0.05	4
Micro (GW)	2	4	1	0.2	0.06	0.09	2	0.4	0.10	2	11
Mini (GW)	3	6	1	0.2	0.02	0.06	4	0.5	0.06	5	20
Small (GW)	3	5	0.9	0.04	0.002	0.01	3	0.2	0.008	6	18
Medium (GW)	0.9	5	0.2	0	0	0	0.9	0	0	1	9
Large (GW)	0	1	0.1	0	0	0	0	0	0	0.1	2
Total per island (GW)	10	21	4	0.5	0.1	0.2	13	1	0.2	14	64
MERIT											
Hydropower capacity	Sumatra	Kalimantan	Jawa	NTT	NTB	Bali	Sulawesi	Maluku	Maluku Utara	Papua	Total per plant
Pico (GW)	0.03	0.05	0.02	0.002	0.001	0.001	0.01	0.002	0.001	0.02	0.1
Micro (GW)	2	2	1	0.1	0.02	0.1	1	0.1	0.02	1	8
Mini (GW)	6	6	2	0.1	0.02	0.1	4	0.1	0.01	7	25
Small (GW)	6	6	1	0.01	0.01	0.03	4	0.03	0	16	33
Medium (GW)	1	5	0.3	0	0	0	1	0	0	6	13
Large (GW)	0.3	0.5	0.1	0	0	0	0	0	0	0.4	1
Total per island (GW)	15	19	4	0.2	0.04	0.2	10	0.3	0.02	31	80
DEMNAS											
Hydropower capacity				NTT		Bali		Maluku			
Pico (GW)				0.03		0.01		0.2			
Micro (GW)				0.4		0.1		0.6			
Mini (GW)				0.2		0.06		0.6			
Small (GW)				0.04		0.02		0.2			
Medium (GW)				0		0		0			
Large (GW)				0		0		0			
Total per island (GW)				0.6		0.2		2			

Table 9 Annual energy production based on technical potential result

USGS

Annual energy	Sumatra	Kalimantan	Jawa	NTT	NTB	Bali	Sulawesi	Maluku	Maluku Utara	Papua	Total per plant
Pico (GWh)	300	630	360	65	30	29	31,100	67	31	470	33,100
Micro (GWh)	17,800	33,200	9,600	1,900	530	820	16,400	3,200	830	15,800	100,400
Mini (GWh)	30,000	49,600	10,700	1,800	180	506	31,100	4,600	560	42,500	171,900
Small (GWh)	30,300	45,900	7,500	380	14	76	24,900	2,000	67	49,900	161,500
Medium (GWh)	8,200	47,700	1,400	0	0	0	7,700	0	0	11,900	77,000
Large (GWh)	1,400	10,600	1,100	0	0	0	0	0	0	1,200	14,400
Total per island (GWh)	88,000	187,600	30,600	4,100	750	1,400	111,200	9,800	1,400	121,700	558,300

MERIT

Annual energy	Sumatra	Kalimantan	Jawa	NTT	NTB	Bali	Sulawesi	Maluku	Maluku Utara	Papua	Total per plant
Pico (GWh)	260	410	142	20	8	9	121	22	5	173	1,100
Micro (GWh)	16,100	21,500	7,500	590	188	720	11,000	992	140	11,200	70,200
Mini (GWh)	50,500	52,100	16,300	950	135	708	35,400	1,000	65	59,700	217,100
Small (GWh)	52,700	29,800	9,100	95	54	260	35,800	262	0	138,300	286,600
Medium (GWh)	7,200	41,700	2,700	0	0	0	7,900	0	0	55,600	116,300
Large (GWh)	2,500	4,400	1,100	0	0	0	0	0	0	3,200	11,400
Total per island (GWh)	129,200	149,900	36,800	1,600	385	1,697	90,200	2,200	210	268,100	702,700

DEMNAS

Annual energy		NTT		Bali		Maluku	
Pico (GWh)		255		129		2,100	
Micro (GWh)		3,000		1,200		4,900	
Mini (GWh)		1,700		567		5,200	
Small (GWh)		327		174		2,100	
Medium (GWh)							
Large (GWh)							
Total per island (GWh)		5,200		2,000		14,300	

C. Economic potential results

Table 10 Calculated LCOE in economic potential analysis

	Sulawesi		Bali		Papua		Jawa		Kalimantan	
	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B
USGS										
Lowest [US ¢/kWh]	1	3	2	6	2	2	1	3	1	4
Highest [US ¢/kWh]	19	57	17	45	36	57	19	57	19	57
MERIT										
Lowest [US ¢/kWh]	1	3	1.5	5	1	3	1	3	1	3
Highest [US ¢/kWh]	19	57	17	57	19	57	19	57	19	57
DEMNAS										
Lowest [US ¢/kWh]			2	6						
Highest [US ¢/kWh]			17	45						
	BPPmin	BPPmax	BPPmin	BPPmax	BPPmin	BPPmax	BPPmin	BPPmax	BPPmin	BPPmax
	6.58	16.55	6.23	13.29	10.23	19.25	5.82	19.25	8.54	10.56

	Sumatra		NTB		NTT		Maluku		Maluku Utara	
	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B
USGS										
Lowest [US ¢/kWh]	1	3	3	10	3	8	3	5	3	8
Highest [ct $/kWh]	19	57	19	57	19	57	19	57	19	57
MERIT										
Lowest [US ¢/kWh]	1	3	2	5	2	6	2	5	3	9
Highest [US ¢/kWh]	19	57	19	57	19	57	19	57	19	57
DEMNAS										
Lowest [US ¢/kWh]					3	9	2	7		
Highest [US ¢/kWh]					23	69	23	69		
	BPPmin	BPPmax	BPPmin	BPPmax	BPPmin	BPPmax	BPPmin	BPPmax	BPPmin	BPPmax
	6.83	19.25	11.77	12.63	11.22	14.74	8.81	17.84	8.81	17.84

Table 11 National economic potential and per island

	Sulawesi		Bali		Papua		Jawa		Kalimantan		Sumatra		NTB		NTT		Maluku		Maluku Utara	
Total per island	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B	Scen. A	Scen. B
USGS																				
P [GW]	9	4	0.2	0.02	14	14	4	1	17	5	10	4	0.1	0.002	0.5	0.1	1	0.4	0.2	0.03
E [GWh]	80400	30800	1300	84	120000	119800	30800	10500	153000	42000	88100	38700	640	20	4100	565	9900	3100	1400	255
Scen. A E [TWh]	490																			
Scen. B E [TWh]	240																			
MERIT																				
P [GW]	10	5	0.2	0.03	31	17	4	2	19	6	15	7	0.04	0.009	0.2	0.1	0.3	0.1	0.02	0.005
E [GWh]	90300	40500	1660	250	268500	147500	37000	15800	165600	50200	129400	62600	350	76	1600	480	2300	790	209	42
Scen. A E [TWh]	690																			
Scen. B E [TWh]	310																			
DEMNAS																				
P [GW]			0.1	0.01											0.3	0.03	1	0.2		
E [GWh]			920	69											2900	300	7400	1943		