Beyond 443 GW

Indonesia's infinite renewables energy potentials

IMPRINT

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Foreword

Indonesia, as an archipelago country located in the equator and having tropical climate, has an abundant amount of renewable energy potentials. This country has solar radiation all year long, water flowing in the river everyday, wind blows every hour, and biomass feedstock available every month that must be harnessed as the sources of power. However, until now, more than 60% of electricity demand is still supplied by fossil fuel based power plants and renewable energy technical potential stated in the National Energy Plan is utilized only 2.4% until 2020. The hidden renewable energy potentials are indeed can be used for completing the electricity demand and achieving zero emission target, respectively.

The latest Electricity Supply Business Plan (Rencana Umum Penyediaan Tenaga Listrik, RUPTL) 2021-2030 mentions that the share of new installed capacity of renewable in 2030 will be 51.6% with the highest share from hydropower (26% of total new installed capacity). Solar power, with currently known potential of 207 GW but used only 0.1% in 2020, will have 4.68 GW additional installed capacity in 2030, which is still far from its maximum capacity, on one hand. On the other hand, IESR's report entitled "Beyond 207 Gigawatts: Unleashing Indonesia's Solar Potential" proves that Indonesia has actually extremely high potential of solar power. This finding raises the questions on the potential of solar power and other renewable energy sources.

This study aims to provide a comprehensive methodology to estimate the technical capacity of renewable energy in Indonesia, which can give insights for governments, stakeholders, experts, and non-technical readers. Renewables, especially solar and wind, are available in every island. Even the biomass and mini hydro are also exist in many provinces in Indonesia. These facts benefit Indonesia, as an archipelago country, to provide clean and cheap electricity from its local resources. In the medium to long term, the integrated inter-island grid could push for higher renewable energy integration. This study also provides a detailed technical capacity of each technology for each province to show that the decentralization of the electricity system is not an impossible feat for Indonesia electricity system is not impossible in Indonesia.

Jakarta, October 2021

Fabby Tumiwa
Executive Director

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Executive Summary

Indonesia's NDC and net zero emission targets are not inline with the Paris Agreement's goal. Higher mitigation ambition requires Indonesia to transform fossil fuel-based power systems to clean energy based power systems. Recent official figures of national renewable energy resource potential does not illustrate an abundant potential of Indonesia's natural resources that can be utilized to reach zero emission by the mid of this century. Moreover, the stated potentials are not followed by a detailed explanation on how those potentials are obtained, which can help the public to evaluate the potential of renewable energy locally.

This study aims to provide a comprehensive methodology and estimations on the potential of renewable energy in Indonesia. Power sources used in this study are solar-, wind-, and micro- to small-hydropower. Biomass is also used to complement the variability of three aforementioned sources that highly depend on the weather conditions or so called Variable Renewable Energies, VREs. Additionally, Pumped Hydro Energy Storage (PHES) potential, as a natural battery, is considered as an option to supply the energy deficit when the demand is higher than the supply.

We use a GIS-based method to choose the best locations where we can apply renewable energy technologies. The results show that we can have an installed capacity of solar up to 7,714.6 GW if there is no restriction in the surface coverage utilization, 28.1 GW of hydropower if we allow to build more than one micro to small hydropower plants in a tributary, and 106 GW of wind power if we use minimum 6 m/s of wind speed at 50 meters. Even when we apply some restrictions for the sake of ecosystem sustainability and robust production estimation, we can supply the power demand using 6,749.3 GW from solar power, 6.3 GW from micro to small hydropower, and 25 GW from wind power. For complementing solar-, wind-, and hydropower, there are technical potential of 30.73 GW from biomass and 7,308.8 GWh from Pumped Hydro Energy Storage.

With this study, we expect that the government updates Indonesia's renewable technical potential data and reviews them regularly as the technologies mature. Thorough and comprehensive mapping of actual natural resources will show not only the abundant potential, but also the corresponding areas to develop and the subsequent potential renewables project pipelines. The government and experts can also complement the map with updated data on intermittency, variability, and grid assessment, including the forecasted data. Such comprehensive data is able to provide insights to stakeholders to produce a more robust project plan considering the impact of climate change and grid readiness on the opportunities to deploy renewable energy in Indonesia. Moreover, the government and stakeholders must consider decentralized power systems and connected islands as two ways to provide the electricity powered by renewable energy to all islands since there are neglected renewable energy potentials outside the main island, Java.

Scenario 1

Solar photovoltaic
(rooftop, ground mounted, and floating)
7,714.6 GW

Pumped Hydro Energy Storage
7,308.8 GWh

Onshore wind power
106 GW
at 50 m hub height
–
88 GW
at 100 m hub height

Biomass power
(only from crop wastes and wooden biomass)
30.73 GW

Micro- to small-hydro-power
with the capacity ≤ 10 MW
28.1 GW

Scenario 2

Solar photovoltaic
(rooftop, ground mounted, and floating)
6,749.3 GW

Pumped Hydro Energy Storage
7,308.8 GWh

Onshore wind power
25 GW
at 50 m hub height
–
19.8 GW
at 100 m hub height

Biomass power
(only from crop wastes and wooden biomass)
30.73 GW

Micro- to small-hydro-power
with the capacity ≤ 10 MW
6.3 GW

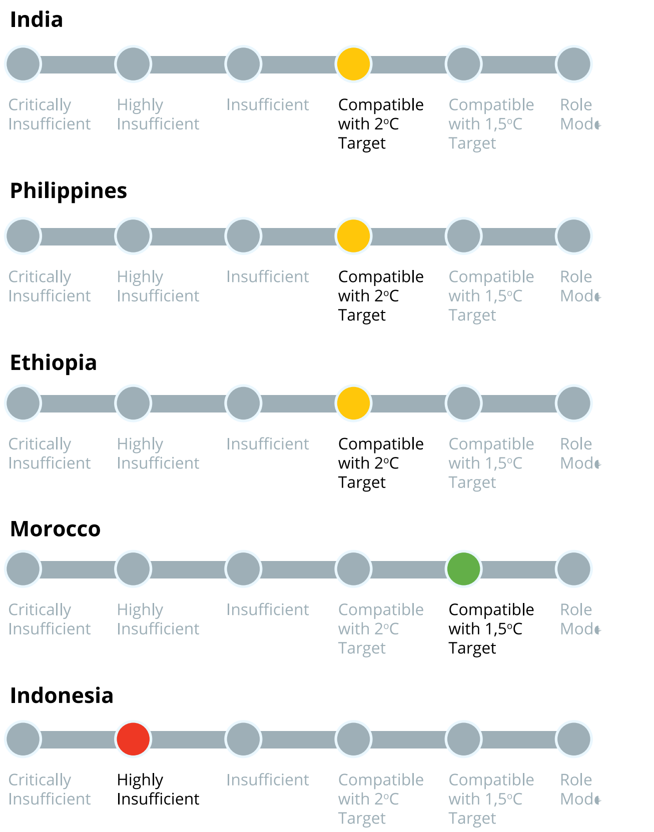
Total technical potential capacity per technology that can be applied in Indonesia

Introduction

High deployment of renewable energy to reach net zero target of Indonesia

Indonesia declared its commitment to climate change following the Paris Agreement by submitting a Nationally Determined Contribution (NDC) to the The United Nations Framework Convention on Climate Change (UNFCCC) secretariat and stipulating Law (Undang-undang, or UU, in Indonesia) no. 16/2016. Both documents state that Indonesia will lower its emission 29% below Business as Usual (BAU) level in 2030 as the unconditional target and 41% below BAU as the conditional target. The Medium Term National Development Plan (or so called Rencana Pembangunan Jangka Menengah Nasioanal, RPJMN) supports this ambition by stating that Indonesia can reach 27.3% lower emission than BAU in 2024. To reach this target, Indonesia wants to apply 23% renewable energy in the total primary energy share in 2025 and 31% in 2030. However, until 2021, those renewable energy targets are still far from the expectation and coal still dominates more than 60% of total electricity shares. Following this update, the states in their Long Term Strategy document that net zero that net zero emissions in all sectors can be reached in 2060 or sooner, without stating the optimal Indonesia's capability to answer how soon it can be (Ministry of Environment and Forestry of Indonesia, 2021).

Indonesia's NDC and net zero emissions targets seem an ambitious target. However, compared to the NDC target of other developing countries aligning with the Paris Agreement, such as India, Philippines, Ethiopia, and Morocco, Indonesia's target is seen as a highly insufficient target (Figure 1). The declaration of the net zero emissions target of Indonesia is also later than other countries and the global target (Table 1).



Source: NDC Climate Action Tracker (https://climateactiontracker.org/climate-target-update-tracker/)

Figure 1. The Indonesia's climate targets compared to other countries for NDC target

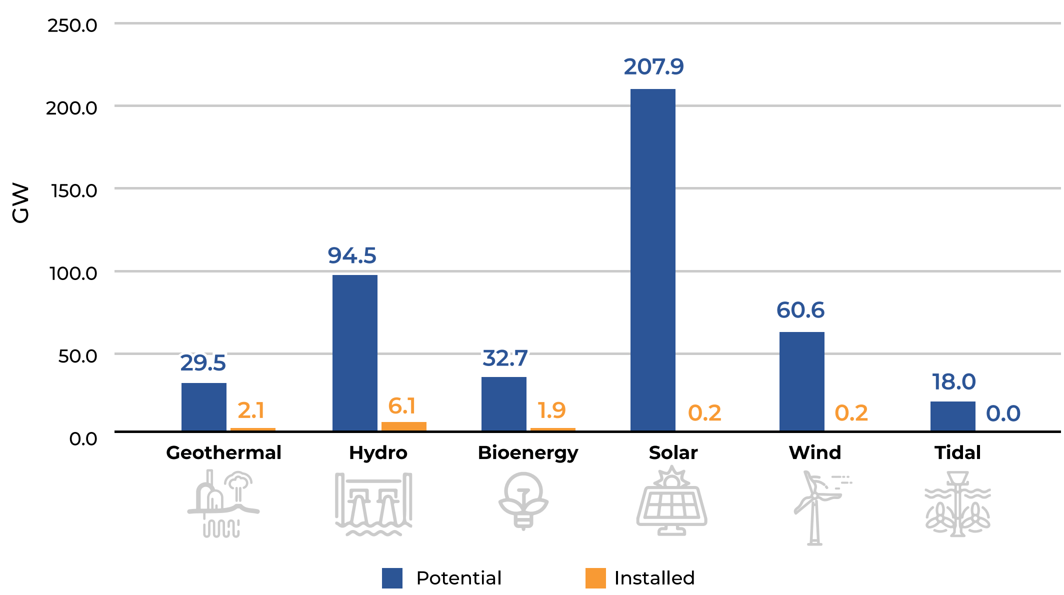
Table 1. Indonesia's net zero target based on Long term Strategy document compared to other countries' target. The global average ability to reach net zero emission based on cost-optimal method is modeled by van Soest et al. (2021)

Area and country	Target
World average	2060
Indonesia	2060
China	2060
Japan	2065
Russia	2060
EU	2050
USA	2050
Turkey	2053
Canada	2050
Brazil	2050

By deploying around 1,700 GW of renewable energy, Indonesia can supply the electricity demand with 100% renewable energy and reach net zero emission before 2060 respectively, in 2050 at the exact year, with the main contribution from 1,492 GW of solar PV (88% of the primary energy mix), 40 GW of hydropower, and 19 GW of geothermal (IESR, 2021b). Utilizing a high share of renewable energy will also give a positive impact on the economic sector. According to IESR (2021b), the cumulative annual system cost from renewable energy-based systems in 2050 is 20% cheaper than fossil fuel-based systems. The capital expenditure (CAPEX) for installing new renewable energy power plants will also be cheaper in the future (i.e. CAPEX of rooftop PV for residential areas will remain only 498.3 USD/kW in 2050 from 1,100 USD/kW in 2020).

Indonesia's national energy plan (Rencana Umum Energi Nasional, RUEN) as officiated in Presidential Regulation No. 22/2017, mentions that Indonesia has the potential of 29.5 GW of geothermal power, 75 GW of large hydropower, 19.4 GW of mini and micro hydropower, 32.7 GW of bioenergy, 207 GW of solar power, 60.6 GW of wind power, and 18 GW of tidal power. From the total potential of 443.2 GW from renewable energy, only 10.5 GW have been deployed in 2020 (Ministry of Energy and Mineral Resources Republic Indonesia, 2021), detailed in Figure 2. These expected potentials must be re-examined because IESR (2021) states that the potential of solar power is 37 times higher than the one stated in RUEN, which can be a proof that Indonesia can actually supply its electricity demand with high share, or even 100%, renewable energy. Based on those gaps, this study aims to provide a comprehensive GIS-based re-examination on the potential of renewable energy in Indonesia that can be a proof that Indonesia has a great renewable energy potential.

Indonesia's installed capacity compared to the estimated potential capacity of renewable energy in 2019



Source: RUEN for potential capacity and Ministry of Energy and Mineral Resources Republic Indonesia (2021) for installed capacity in 2020

Figure 2. The updated of installed capacity in 2020 compared to the estimated potential capacity of renewable energy stated in RUEN

Methodology

A GIS-based technical potential estimation

The potential locations of each type of renewable energy are chosen by the filtering method illustrated in Figure 3, which basically excludes protected areas (UNEP-WCMC, 2019), water bodies, roads, electricity networks, airports, and other restricted areas for each source detailed in Table 2. After obtaining the suitable areas, we can calculate the technical potential of each renewable energy source using the equations in Table 3. We focus on the technical capacity in this study and provide also formulas for calculating the technical generation for readers in Table 3. Renewable energy considered in this study is solar, wind, hydro, and biomass. Moreover, we also provide technical energy storage capacity estimation from Pumped Hydro Energy Storage (PHES) grade A, which is the cheapest and easiest to be installed, that is originally modeled by Stocks et al. (2021, 2019) and furtherly filtered with the requirements listed in Table 1. To ensure that PHES can be applied using an open-loop scheme where the lower reservoir is a dam, we specifically choose the locations that have lower reservoirs in the water bodies.

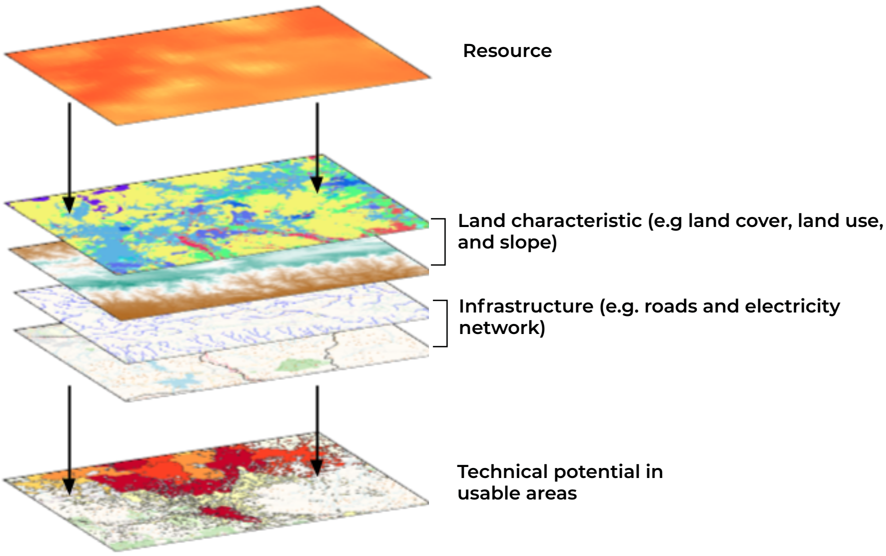


Figure 3. Exclusion method to calculate technical potential in usable areas

Table 2a. Type of land covers, landforms, and natural features that are excluded from the suitable area consideration for calculating solar, wind, and hydropower in this study. 'X' defines the conditions that are excluded and 'O' are the ones that are included in the suitable areas and/or conditions

	Type	Solar power	Wind power	Hydropower	Source
Land cover	Protected areas	X	X	X	UNEP-WCMC (2019)
	Roads	X	X	X	-
	Electricity networks	X	X	X	-
	Airports	X	X (< 4000 m from airports)	X	Regulation of Ministry of Transportation no. 44/2005
	Harbours	X	X	X	IESR (2021a)
	Rivers	X	X	O	IESR (2021a)
	Lakes	X	X	X	IESR (2021a)
	Dams	O (only for floating PV)	X	X	IESR (2021a), NREL (2021), and Regulation of the Minister of Public Works and Public Housing no. 6/2020)
	Forests	X	X	X	UNEP-WCMC (2019), IESR (2021a), and NREL (2009)
	Agriculture lands	X	X	X	IESR (2021a) and NREL (2009)
	Shrubs	O	O	X	IESR (2021a) and NREL (2009)
	Savannahs	O	O	X	IESR (2021a) and NREL (2009)
	Bare lands	O	O	X	IESR (2021a) and NREL (2009)
	Mining areas	O	O	X	IESR (2021a) and NREL (2009)
	Settlements areas	O	X (< 500 m from residential areas)	X	IESR (2021a), NREL (2009), and (Burton et al., 2001)
	Transmigration areas	O	O	X	IESR (2021a), NREL (2009), and (Burton et al., 2001)
Landform	Plain areas	O (slope < 10deg)	O (slope < 10deg)	X	IESR (2021a), NREL (2009), and (Burton et al., 2001)
	Hilly or mountainous	X	X	O (slope ≥ 2.5 m and at least on 500 masl)	Hidayah et al. (2017) and Sammartano et al. (2019)
Natural conditions	Runoff at least 200 m per month per 1 m2 of map grid (or following the design boundaries)	-	-	O	Hänggi & Weingartner, (2012) and Puspitarini et al. (2020)
	Annual mean wind speed at least 6 and 7.25 m/s at 50 masl and 6.6 and 7.99 at 100 masl	-	O	-	Burton et al. (2001)

Table 2b. Same as Table 2a, but for biomass and PHES

Type		Biomass power	PHES	Source
Land cover	Protected areas	X	X	UNEP-WCMC (2019)
	Roads	X	X	-
	Electricity networks	X	O	-
	Airports	X	X	Regulation of Ministry of Transportation no. 44/2005
	Harbours	X	X	IESR (2021a)
	Rivers	X	O	Blakers et al. (2021) and Stocks et al. (2021)
	Lakes	X	O	Blakers et al. (2021) and Stocks et al. (2021)
	Dams	X	O	IESR (2021a), NREL (2021), and Regulation of the Minister of Public Works and Public Housing no. 6/2020)
	Forests	X	X	UNEP-WCMC (2019), IESR (2021a), and NREL (2009)
	Agriculture lands	O	X	Global Forest Watch (https://www.globalforestwatch.org/map/)
	Shrubs Savannahs Bare lands Mining areas	X (following the current commodity map)	O (close to water bodies)	Global Forest Watch (https://www.globalforestwatch.org/map/), Blakers et al. (2021) and Stocks et al. (2021)
	Settlements areas	X	X	-
	Transmigration areas	X	O (close to water bodies)	-
Landform	Plain areas	O (slope < 10deg)	O	Blakers et al. (2021) and Woo et al. (2018)
	Hilly or mountainous	O (critical areas)	O	Blakers et al. (2021) and Woo et al. (2018)
Natural conditions	Runoff at least 200 m per month per 1 m2 of grid (or following the design boundaries)	-	-	-
	Annual mean wind speed at least 7.25 m/s at 50 masl and 7.99 at 100 masl	-	-	-

After obtaining the suitable land from the above-mentioned methods, we calculate the technical capacity of each source using the inputs in Table 3 and equations in Table 4. In this study, solar photovoltaic power plants (PV) is the first resource that we calculate its potential. The inputs of its technical potential calculation is the suitable coverage area and a constant power density parameter, which is a capacity for an area unit. We assume that the power density for each nameplate capacity is 0.041 GWp/km^2 according to (NREL, 2013b). Please note that this is an inflexible assumption and readers may apply other power density assumptions for each location. We then calculate the generated power per year by multiplying the technical potential with a map of estimated power generated by PV per 1 kWp from Global Solar Atlas (https://globalsolaratlas.info/). This map is modeled by considering the PV system characteristics (e.g. panel type, tilt angle, capacity, and azimuth) and weather conditions (e.g. temperature and solar radiation) for each specific longitude and latitude. We create two scenarios in this study to estimate the technical potential of solar power; i) All areas covered by shrubs, savannahs, residential areas, bare lands, minings, transmigration areas, and dams can be covered by solar panels and ii) Only 27% of rooftop area (NREL, 2013a) and 5% of dam surface (Regulation of the Minister of Public Works and Housing No. 6/2020) can be covered by solar panels.

For wind power potential calculation as our second potential resource, we consider only the horizontal turbines with hub heights of 50 and 100 meters and thus use the wind speed limitation accordingly. We use the wind speed, power density, and capacity factor data from Global Wind Atlas (https://globalwindatlas.info/) as the inputs of our calculations. We validate the robustness of Global Wind Atlas by computing the correlation between wind speed map from this website with the map from windPROSPECTING sites (http://indonesia.windprospecting.com/), which is the map produced by EMD International A/S Denmark and has been used by Indonesia's Ministry of Energy and Mineral Resources. The results show that the correlation between both maps is 0.78 meaning that both data have high correlation and thus we can use the data of Global Wind Atlas as planned.

Before calculating wind power potential, we firstly determine the minimum mean annual wind speed that we take into account. Since the wind speed data from Global Wind Atlas is a mean annual wind speed data, we use the minimum wind speed of 7.25 m/s for the hub height of 50 meters as described in Burton et al. (2001). Based on our discussion with researchers of Directorate General of New Renewable Energy and Energy Conservation of Indonesia, we build another scenario for considering the minimum mean annual wind speed of 6 m/s at 50 meters into the calculation since the boundary set by Burton et al. (2001) may not be suitable for Indonesia, which its wind speed is not as high as foreign countries. We thus use minimum mean annual wind speed of 6 m/s in our first scenario and minimum mean annual wind speed of 7.25 m/s in our second scenario. We also calculated the wind speed in 100 meters using equation of $U(z)=U(50)\cdot(z/50)^{0.14}$, where $U(z)$and $U(50)$ is the mean annual wind speed at z and 50 m of hub height, resulting in the minimum mean annual wind speed used in this study at 100 meters of hub height is 6.6 m/s and 7.99 m/s. We then filter the suitable areas with the areas having the aforementioned minimum wind speed and calculate its wind power technical potential by multiplying the power density in that location with the swept areas of the rotor. The distance between each turbine is at least twice of the rotor diameter according to Burton et al. (2001). Rotor diameters used in this study are assumed to be equal to the hub heights, which are 50 and 100 m. For each location, we compute the generated power from its calculated technical potential and capacity factor from Global Wind Atlas. Readers may take a note on other wind turbine technologies (i.e. vertical wind turbines) that are able to be operated at the low wind speed, which are not considered in this study because those technologies are still new and the price may not be as cheap as the commonly known horizontal wind turbines.

The third power resource that we calculate its potential is hydropower using run-of-river technology, whose main calculation input is surface runoff from ERA5 climate reanalysis. For ensuring the robustness of this global scaled data, we validate it with the observed data from Global Runoff Data Center.

According to Table 2, we choose locations for micro to small hydropower plants that have the monthly flow average between two lowest and highest boundaries, which are 95th percentile of the monthly flow in a basin as the lowest flow that must remain in the river for the sake of ecological protection in the river during the dry season and 2nd percentile of the monthly flow in a basin as the highest flow that can be diverted in the plants to protect the turbine during the flood in rainy or monsoon season (François et al., 2018; Hänggi & Weingartner, 2012; Puspitarini, François, Zaramella, et al., 2020). We create two scenarios in this study; i) More than one hydropower plant allowed in a river basin to optimize its potential and ii) Only one hydropower plant allowed in a river basin to protect the ecosystem and social activities, commonly located downstream. Other variables needed for calculating the technical capacity of run-of-river hydropower are listed in Table 4. It must be noted that we compute only the micro to small sizes of hydropower, with the maximum capacity of 10 MW, because there are several issues that must be taken into account for installing large hydropower, such as the land acquisition, social activities, and other environmental constraints.

The last resource that we consider in this study is biomass feedstock, which can be the complementary of solar, wind, and hydropower that highly depend on the weather fluctuations (Puspitarini, et al., 2020). We take crop wastes, including wastes of coffee, chocolate, rice, and palm, and wooden biomass feedstocks from Acacia in this study and do not take the potential of palm oil into account because we aim to optimally use the crops and fast growing forest products. We use the commodity map from Condro et al. (2020) for crops and Global Forest Watch for Acacia (https://www.globalforestwatch.org/map/) for calculating the biomass production per year by multiplying the commodity coverage with the production per m^2 for each commodity and its harvested cycle per year (Table 4). It has to be noted that we consider only the existing areas used for planting the aforementioned plantations and do not use the opportunity to use any other landforms (e.g. bare lands and shrubs) to open new plantation areas. We then calculate the technical potential of each commodity by multiplying the production per year with calorific value, power plant efficiency, and the percentage of wastes from the whole fruit or crop. All additional variables information are detailed in Table 5 and 6.

Table 3. Input data for the calculation of technical potential and generated power from each renewable energy source

Type	Variables	Sources	Temporal resolution	Spatial resolution	Unit
Solar	Land cover	Land coverage 2017 from the Ministry of Environment and Forestry	-	125 meters (1:250.000)	-
	Daily average of estimated power generated by PV per 1 kWp	Global Solar Atlas (https://globalsolaratlas.info/)	12 x 24 (month x hour) profiles	1 kilometers and resampled into 250 meters	kWh/kWp
Wind	Wind speed	Global Wind Atlas (https://globalwindatlas.info/)	Mean annual	250 meters	m/s
	Wind power density				W/m^2
	Capacity factor				%
Hydro	Surface runoff	ERA5 reanalysis	Mean daily	0.1° (~11.1 kilometers) and resampled into 250 meters	meter
Biomass	Commodity coverage map	Condro et al. (2020) and Global Forest Watch (https://www.globalforestwatch.org/map/)	-	30 meters	-

Table 4. Technical potential calculation for each type of renewable energy sources

Type	Equation for calculating technical potential	Explanation of each variables
Solar	$Cap_{PV} = A \cdot PD$ $E_{PV} = Cap_{PV} \cdot PVOUT \cdot 365 \cdot 1/1000$	Cap_{PV} is the technical capacity in GWp, A is the suitable coverage in km^2, PD is power density (0.041 GWp/km^2 for PV according to NREL, 2013b), E_{PV} is the technical generation in GWh, and $PVOUT$ is an daily average of estimated power generated by PV per 1 kWp, or well-known as capacity factor
Wind	$U(z) = U(50) \cdot (z/50)^{0.14}$ $Cap_{wind} = PD \cdot A$ $A = \pi(0.5 \cdot \varphi)^2$ $E_{wind} = Cap_{wind} \cdot CF$	U(z) and U(50) is the mean annual wind speed at z and 50 m of hub height, Cap_{wind} is wind power potential capacity in Watt, PD is the power density in W/m^2, A is the areas of the rotor in m^2, φ is the diameter of the rotor in m, E_{wind} is the generated power in Wh, and CF is the capacity factor in % per year. Global Wind Atlas provides the map of power density and capacity factor of ICE type I, II, and III. In this calculation, we use turbine type III because it is typically used in the areas with low wind speed (Lledó et al., 2019)
Hydro	$Cap_{shp} = \eta \cdot \rho \cdot g \cdot h \cdot Q$ $E_{shp} = Cap_{shp} \cdot CF$	Cap_{shp} is the potential capacity of pico to small sized hydropower plants in kW, η is power plant efficiency that is assumed to be 75%, ρ is water density in kg/m^3, h is the head between inlet and outlet that is assumed to be 2.5 m, Q is runoff in m per month per m^2 of grid, E_{shp} is the generated power in kWh, and CF is the capacity factor that is 50%.
Biomass	$Prod = A \cdot \beta \cdot \gamma$ $Cap_{biomass} = Prod \cdot \alpha \cdot \eta \cdot \vartheta$ $E_{biomass} = Cap_{biomass} \cdot CF$	$Prod$ is total production in each area (ton), A is the area (m^2), β is the production per m^2 for each plant, γ is the harvested cycle per year, $Cap_{biomass}$ is the generated power from biomass power plant (kW), α is the calorific value (kJ/kg), η is the power plant efficiency assumed to be 25%, and ϑ is the percentage of wastes from the whole fruit or crop. β, γ, and ϑ are detailed in Table 5 and 6. $E_{biomass}$ is the generated power (kWh/year) and CF is capacity factor that can assumed to be 70%.

Table 5. Commodity production per hectare and its cycle

Commodity	Crops production per hectare		Harvesting cycle per year	
	Production (ton/ha)	Source	Cycle (/year)	Source
Chocolate	0.5	Badan Pusat Statistik (2020)	2	Fahmid (2013)
Coffee	0.6	Badan Pusat Statistik (2020)	1-2	Kementerian Pertanian (2020)
Paddy	5	Kementerian Pertanian (2019)	3-4	Kawanishi & Mimura, (2015) and Sumarno (2006)
Palm	3	Badan Pusat Statistik (2020)	12-24	Lee et al. (2014)
Acacia	20	Private archive of GGGI	1-2	Private archive of GGGI

Table 6. Detailed calorific value and waste percentage for each commodity

Commodity	Type of waste	Calorific value per kg		Waste percentage per kg	
		Calorific value (kJ/kg)	Source	Waste percentage (%)	Source
Chocolate	Pod husk	16,670	Martínez-Ángel et al. (2015)	67	Campos-Vega et al. (2018)
Coffee	Husk	18,340	Miito & Banadda (2017)	50	Oliveira & Franca (2015)
Paddy	Husk	12,980	Ozturk & Bascetincelik (2006)	20	Singh (2018)
Palm	Kernel	23,605	Paul et al. (2015)	40	Koura et al. (2016)
	Fiber	14,512		11.5	
	Empty fruit bunch	17,400		25.5	
Acacia	Wood	20,083	Private archive of GGGI	100	Private archive of GGG

Results

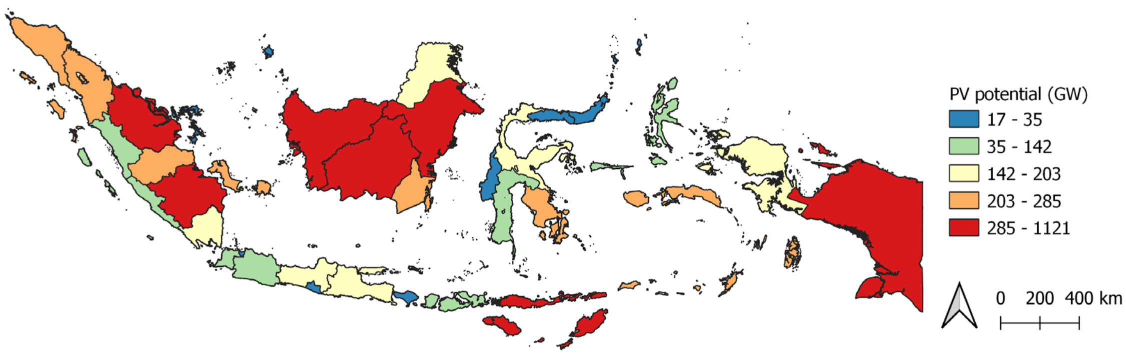
Powering Indonesia with more than 7,000 GW from renewable energy sources and more than 7,000 GWh from batteries is viable

1. Solar power technical potential

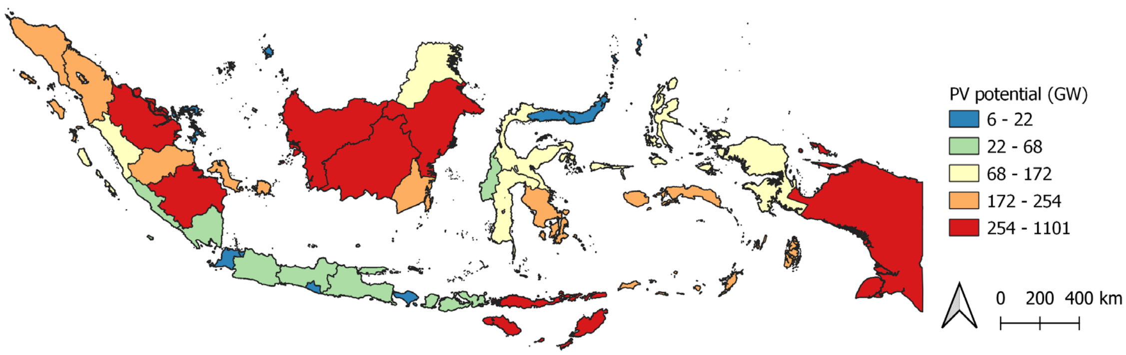
With the mean global horizontal irradiation of 3.45-5.74 kWh/m^2, we found that solar power has the highest potential among other renewable energy sources. Indonesia has a technical potential of up to 7,714.6 GW from solar power by including all areas covered by shrubs, savannah, bare land, residential area, mining, transmigration area, dam and up to 6,749.3 GW by restricting only 27% of rooftop and 5% of dam surface allowed to be covered by solar panels (Table 7, detailed technical capacity for each province can be read in IESR, 2021a). The highest potential comes from areas covered by shrubs in both scenarios because of its total areas. If Indonesia will be able to use this potential optimally, zero emission in the power sector is certainly possible to be achieved in 2050 (IESR, 2021b). Three uppermost provinces with high solar power potential are provinces in Kalimantan, Nusa Tenggara, and Papua (Figure 4, Tabel 8).

Table 7. The technical capacity potential of solar power in each type of area coverage from Scenario 1 and 2

Land use type	Technical capacity from Scenario 1 (GWp)	Technical capacity from Scenario 2 (GWp)
Shrubs	4,179.4	4,179.4
Bare land	1,183.6	1,183.6
Residential area	1,312.3	354.3
Ex-mining	280.4	280.4
Savannah	632.1	632.1
Transmigration areas	112.2	112.2
Dams	14.6	7.3
Total	**7,714.6**	**6,749.3**



(a)



(b)

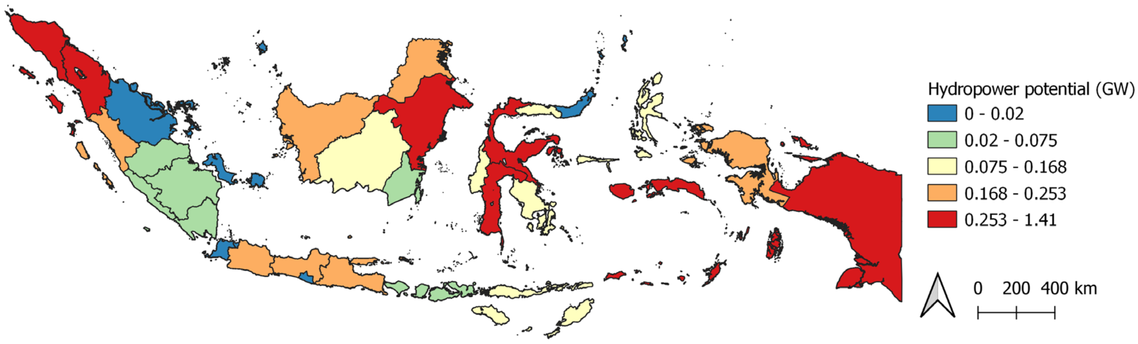
Figure 4. Technical potential of solar power in which we optimally use all areas without any restrictions (a) and apply some restrictions (b)

Table 8. Technical capacity potential of **solar power** in each province from Scenario 1 and 2

Province	Scenario 1		Scenario 2	
	Suitable Area (km^2)	Technical capacity (GWp)	Suitable Area (km^2)	Technical capacity (GWp)
Aceh	5,295.59	217.12	4,290.77	175.94
Bali	645.08	26.45	282.52	11.60
Banten	948.04	38.87	291.57	11.97
Bengkulu	1,570.06	64.37	1,358.21	55.70
DI Yogyakarta	681.48	27.94	178.92	7.35
DKI Jakarta	571.35	23.43	145.49	5.98
Gorontalo	407.14	16.69	291.42	11.97
Jambi	6,865.42	281.48	6,084.33	249.47
Jawa Barat	3,583.79	146.93	997.33	40.91
Jawa Tengah	4,738.72	194.28	1,322.24	54.23
Jawa Timur	4,876.39	199.93	1,626.23	66.69
Kalimantan Barat	24,359.61	998.74	23,987.24	983.49
Kalimantan Selatan	5,116.24	209.77	4,726.47	193.80
Kalimantan Tengah	14,775.53	605.80	14,303.46	586.46
Kalimantan Timur	27,330.11	1,120.54	26,846.08	1,100.71
Kalimantan Utara	3,481.05	142.72	3,306.72	135.59
Kepulauan Bangka Belitung	5,342.96	219.06	5,099.18	209.08
Kepulauan Riau	630.11	25.83	499.23	20.49
Lampung	3,516.26	144.17	1,584.49	64.98
Maluku	4,960.39	203.38	4,794.44	196.59
Maluku Utara	2,068.81	84.82	1,976.30	81.05
Nusa Tenggara Barat	1,274.86	52.27	989.32	40.58
Nusa Tenggara Timur	8,258.26	338.59	7,621.35	312.49
Papua	14,133.47	579.47	13,938.72	571.50
Papua Barat	3,923.69	160.87	3,647.64	149.57
Riau	7,267.23	297.96	6,376.92	261.47
Sulawesi Barat	678.26	27.81	542.65	22.27
Sulawesi Selatan	2,587.76	106.10	2,098.56	86.06
Sulawesi Tengah	4,138.91	169.70	3,821.07	156.68
Sulawesi Tenggara	5,022.65	205.93	4,761.77	195.25
Sulawesi Utara	507.47	20.81	341.90	14.04
Sumatera Barat	2,058.79	84.41	1,774.17	72.76
Sumatera Selatan	10,759.73	441.15	9,500.07	389.52
Sumatera Utara	5,786.37	237.24	5,196.11	213.06
Total	**188,161.57**	**7,714.62**	**164,602.92**	**6,749.30**

2. Micro- to small-hydropower technical potential

For fully optimizing the potential of renewable energy in Indonesia, hydropower can be used to complement the production of solar power that has a high hourly variability due to the cloud coverage, temperature, and humidity variability. It must be noted that hydropower plants analyzed in this study are only micro to small hydropower with the capacity less than 10 MW. When we do not put any restrictions on the number of micro to small hydropower plants in a river tributary (Figure 5b), the potential of this power source can reach 28 GW with the highest potential from Papua, North Sumatera, West java, and almost all Sulawesi. The results of the second scenario gives us a high value of micro to small hydropower potential in the river networks of Indonesia, but there will be a further impact on the ecosystem since we allow more than one hydropower plant in a river. When we permit only one micro to small hydropower plant in a tributary in the first scenario to ensure the sustainability in the river's ecosystem (Figure 5a), we can power up to 6 GW with high potential in Papua, North Sumatera, and almost all provinces in Sulawesi (Table 9).



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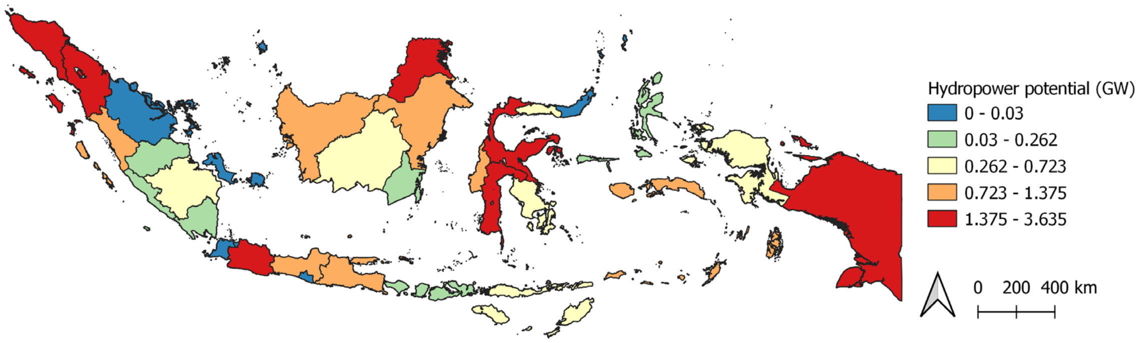


(b)

Figure 5. Technical potential of micro to small hydropower in which with restriction in the number of hydropower plants allowed in a river tributary to consider the changes on ecosystem impact due to the existence of small hydropower (a) and without any restrictions to optimally use the resource (b)

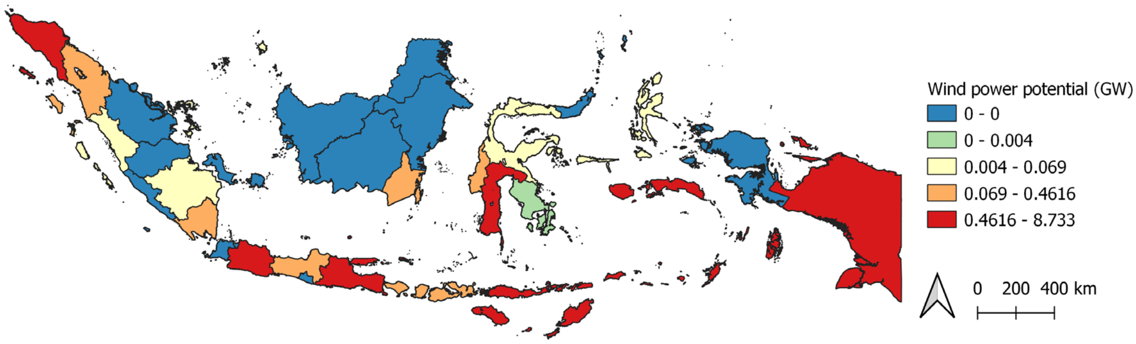
Table 9. Technical potential of **micro to small hydropower** in each provinces using Scenario 1 and 2

Province	Technical potential (MW)	
	Scenario 1	Scenario 2
Aceh	3,380.6	341.8
Bali	256.1	61.4
Banten	24.4	18.1
Bengkulu	97.0	62.2
DI Yogyakarta	15.7	10.1
DKI Jakarta	0.0	0.0
Jambi	185.0	47.7
Jawa Barat	1,404.4	246.0
Jawa Tengah	730.3	215.6
Jawa Timur	846.0	220.9
Kalimantan Barat	934.1	251.2
Kalimantan Selatan	136.1	35.7
Kalimantan Tengah	422.6	95.8
Kalimantan Timur	964.6	254.5
Kalimantan Utara	2,616.6	192.4
Kepulauan Bangka Belitung	0.0	0.0
Kepulauan Riau	0.0	0.0
Lampung	81.3	34.1
Nusa Tenggara Barat	33.9	21.1
Papua	3,635.3	1,409.7
Papua Barat	449.4	170.9
Riau	9.9	9.9
Sumatera Barat	917.1	210.1
Sumatera Selatan	286.7	71.1
Sumatera Utara	2,561.7	363.9
Nusa Tenggara Timur	693.1	154.1
Sulawesi Utara	0.0	0.0
Sulawesi Tengah	2,645.8	567.2
Sulawesi Selatan	1,445.9	329.7
Sulawesi Tenggara	321.7	137.5
Gorontalo	337.0	126.4
Sulawesi Barat	845.4	110.3
Maluku	1,355.8	269.2
Maluku Utara	145.1	89.6
Total	**27,778.5**	**6,127.9**

3. Wind power technical potential

Due to the location of Indonesia, which is in the equator having warm air and low pressure, Indonesia is not as windy as countries in the northern and southern hemispheres. The mean annual wind speed in Indonesia is only 4.9 m/s, while in the Netherlands, as a sample country in the northern hemisphere, is 8.8 m/s according to Global Wind Atlas. Such conditions bind the potential of wind power in equatorial regions. The technical potential of wind power reaches up to 106 GW for hub height of 50 meters and 88 GW for hub height of 100 meters from the second scenario results in which we apply the minimum wind speed value of 6 m/s at 50 meters and 6.6 m/s at 100 meters, as our first scenario.

Wind power potential in Indonesia is 25 GW with 50 m hub height and 19.8 GW with 100 m hub height using the minimum mean annual wind speed of 7.25 m/s at 50 meters and 7.99 m/s at 100 meters based on Burton et al. (2001) as our second scenario. By strictly limiting the wind speed, it is clearly shown that only a couple of provinces have high potentials when we install wind turbines with the 100 meters hub height (Figure 6b). The most abundant potential is in South Sulawesi, Nusa Tenggara, and Maluku (Table 10). We indeed can see that wind power potential can actually be harnessed in almost all provinces in Indonesia, if we use the minimum wind speed of 6 m/s in the first scenario. However, it has to be noted that there will be higher variability of wind speed, with small and frequent wind speed, included if we use this scenario.



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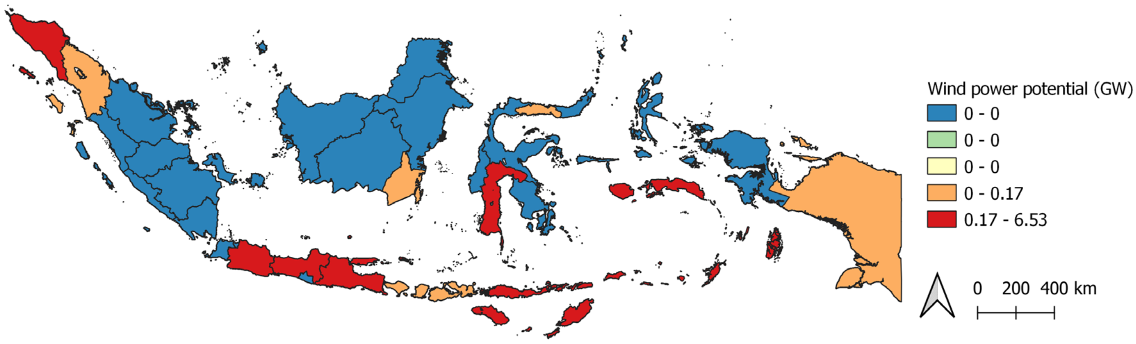

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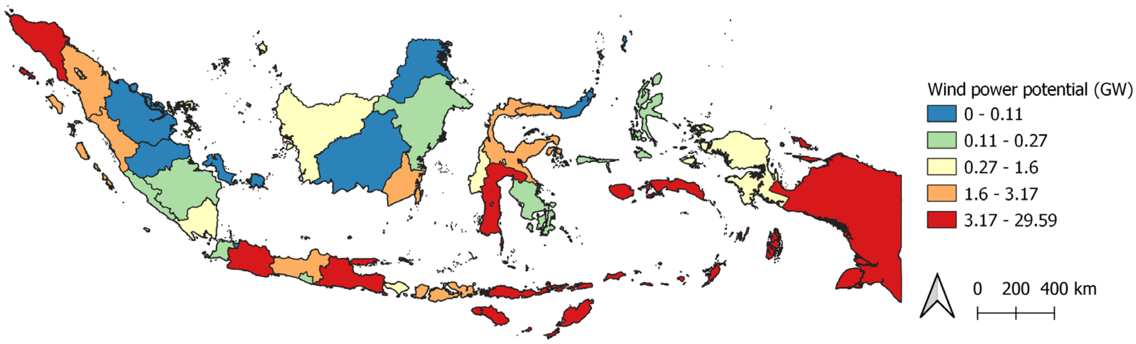

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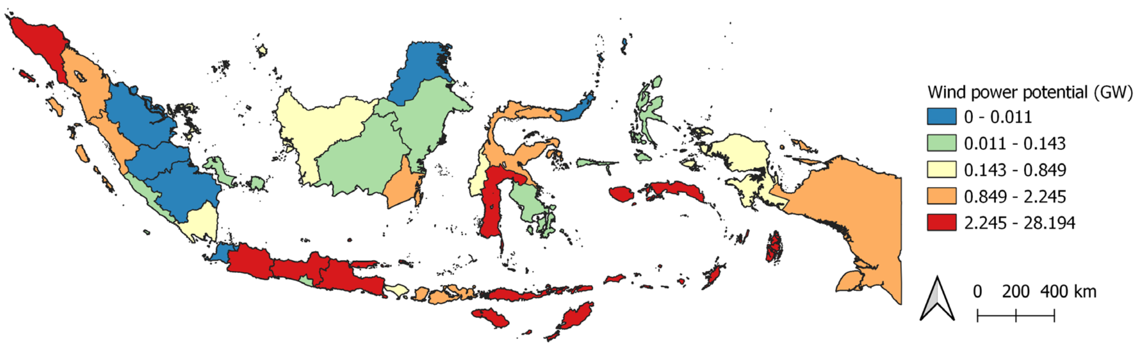


(d)

Figure 6. Technical potential of wind power from scenario 1, with the minimum mean annual wind speed of 7.25 m/s at the 50 meters and 7.99 m/s at 100 meters (a and b), and from scenario 2, with the minimum mean annual wind speed of 6 m/s at the 50 meters and 6.6 m/s at 100 meters (c and d).

Table 10. Technical potential of **wind power** at 50 and 100 m hub height in each province

Province	Technical potential at 50 m (MW)		Technical potential at 100 m (MW)	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Aceh	7,138.0	1,104.5	4,920.2	1,211.1
Bali	445.2	71.5	309.8	20.9
Banten	206.6	0.0	9.4	0.0
Bengkulu	176.8	0.0	97.9	0.0
DI Yogyakarta	176.8	0.0	137.9	0.0
DKI Jakarta	0.0	0.0	0.0	0.0
Jambi	29.4	0.0	0.0	0.0
Jawa Barat	3,712.8	780.3	3,510.7	418.6
Jawa Tengah	2,950.3	444.4	3,052.7	185.3
Jawa Timur	3,498.6	488.2	5,624.9	205.3
Kalimantan Barat	712.0	0.0	372.6	0.0
Kalimantan Selatan	2,154.9	120.4	1,561.2	86.7
Kalimantan Tengah	72.9	0.0	11.8	0.0
Kalimantan Timur	261.0	0.0	83.9	0.0
Kalimantan Utara	59.2	0.0	3.2	0.0
Kepulauan Bangka Belitung	61.5	0.0	37.0	0.0
Kepulauan Riau	300.7	36.2	163.4	0.0
Lampung	525.7	70.4	347.7	0.0
Nusa Tenggara Barat	2,678.1	183.8	1,596.7	34.5
Papua	3,489.9	1,085.2	898.4	161.4
Papua Barat	1,510.0	0.0	652.2	0.0
Riau	14.5	0.0	0.0	0.0
Sumatera Barat	2,256.1	11.9	1,666.3	0.0
Sumatera Selatan	131.6	15.9	2.6	0.0
Sumatera Utara	2,692.7	246.2	1,703.8	38.4
Nusa Tenggara Timur	29,587.8	4,933.0	28,193.8	5,943.8
Sulawesi Utara	0.0	0.0	0.0	0.0
Sulawesi Tengah	2,766.6	15.2	1,705.6	0.0
Sulawesi Selatan	19,686.8	8,732.7	13,192.1	6,525.0
Sulawesi Tenggara	128.7	2.1	66.8	0.0
Gorontalo	1,623.0	65.1	1,434.5	9.7
Sulawesi Barat	400.8	107.2	307.4	0.0
Maluku	15,455.7	6,391.7	15,925.5	4,857.6
Maluku Utara	137.8	20.9	51.1	0.0
Total	**105,042.3**	**24,926.8**	**87,641.1**	**19,698.4**

4. Biomass power technical potential

Biomass power plants, whose feedstocks do not depend highly on the weather conditions unlike solar, wind, and hydropower, or so called Variable Renewable Energies (VREs), can be a complement to solve the variability issues. We focus on the potential of crop wastes and wooden feedstocks in this study (Table 11). Paddy, cacao, palm, and coffee wastes are considered in this study and have the potential of 23.4 GW. Acacia is the only wooden biomass in this study having technical potential of 7.3 GW. Provincial potential is detailed in Table 8. Overall, provinces where we can use optimally their biomass feedstocks are provinces in Sumatra and Kalimantan since their palm production is the highest in Indonesia (Figure 7, Table 12).

Table 11. Biomass power plants technical potential based on their resources

Commodity	Type of waste	Technical potential (GW)
Chocolate	Kernel shell	0.02
Coffee	Poor quality fruit and outer skin	0.03
Paddy	Husk	3.08
Palm	Kernel	12.30
	Fiber	2.20
	Empty fruit bunch	5.80
Acacia	Wood	7.30
	Total	**30.73**

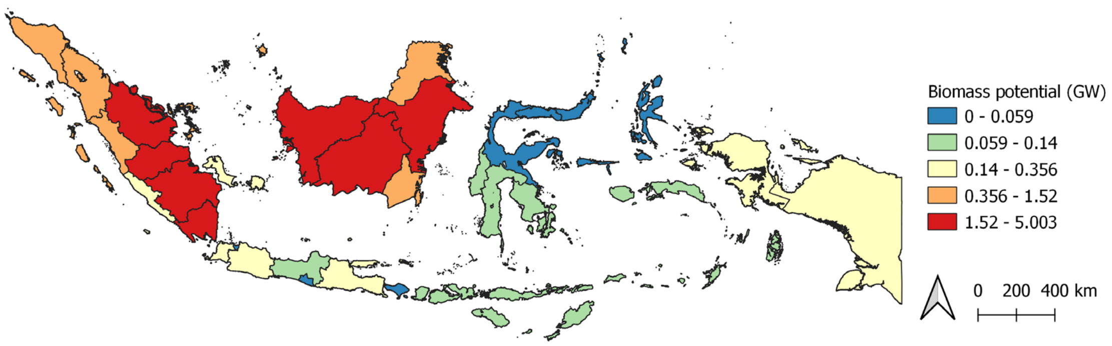


Figure 7. Technical potential of total biomass feedstock containing crop wastes and wood pellets as a complementary of VREs

Table 12. Technical capacity potential of **biomass** for each source in each province

Province	Technical capacity (MW)							
	Palm kernel	Palm fiber	Palm empty fruit bunch	Chocolate	Coffee	Paddy	Acacia	Total
Aceh	491.7	86.9	231.1	6.0	5.8	111.9	0.0	933.4
Bali	0.0	0.0	0.0	0.3	0.4	12.3	2.2	15.2
Banten	185.7	32.8	87.3	0.0	0.2	28.8	1.8	336.6
Bengkulu	188.3	33.3	88.5	0.1	0.8	43.9	0.0	354.9
DI Yogyakarta	0.0	0.0	0.0	0.1	0.2	10.1	0.0	10.4
DKI Jakarta	0.8	0.1	0.4	0.0	0.0	4.6	0.0	5.9
Gorontalo	0.0	0.0	0.0	0.0	0.0	16.2	0.0	16.2
Jambi	591.9	104.6	278.1	0.3	0.3	151.4	930.9	2,057.5
Jawa Barat	111.4	19.7	52.4	1.7	1.2	110.9	59.0	356.3
Jawa Tengah	0.0	0.0	0.0	1.0	1.5	85.7	17.7	105.9
Jawa Timur	0.0	0.0	0.0	0.9	2.1	108.0	53.6	164.6
Kalimantan Barat	1,654.5	292.4	777.5	0.0	0.0	191.1	82.6	2,998.1
Kalimantan Selatan	444.2	78.5	208.7	0.0	0.1	82.8	52.0	866.3
Kalimantan Tengah	1,740.2	307.6	817.8	0.0	0.1	206.3	694.7	3,766.7
Kalimantan Timur	1,137.6	201.1	534.6	0.0	0.1	136.7	384.9	2,395.0
Kalimantan Utara	300.8	53.2	141.3	0.0	0.0	35.9	20.9	552.1
Kepulauan Bangka Belitung	94.6	16.7	44.4	0.2	0.1	75.8	0.3	232.1
Kepulauan Riau	362.9	64.1	170.5	0.1	0.1	64.2	0.0	661.9
Lampung	943.6	166.8	443.4	0.1	0.3	95.3	0.0	1,649.5
Maluku	3.7	0.7	1.7	0.1	0.3	54.2	0.0	60.7
Maluku Utara	0.0	0.0	0.0	0.0	0.0	13.8	0.2	14.0
Nusa Tenggara Barat	0.0	0.0	0.0	0.3	0.3	73.8	0.0	74.4
Nusa Tenggara Timur	0.0	0.0	0.0	0.5	2.1	136.3	0.0	138.9
Papua	213.3	37.7	100.2	0.0	0.0	5.2	0.0	356.4
Papua Barat	89.6	15.8	42.1	0.0	0.0	0.9	0.0	148.4
Riau	1,039.3	183.7	488.4	1.9	0.3	405.1	2,548.5	4,667.2
Sulawesi Barat	52.5	9.3	24.7	0.0	0.5	19.6	0.0	106.6
Sulawesi Selatan	0.0	0.0	0.0	0.1	2.2	107.6	0.0	109.9
Sulawesi Tengah	0.0	0.0	0.0	0.0	1.0	44.3	11.8	57.1
Sulawesi Tenggara	0.0	0.0	0.0	0.1	0.2	64.6	0.0	64.9
Sulawesi Utara	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Sumatera Barat	512.6	90.6	240.9	2.2	3.3	109.1	40.3	999.0
Sumatera Selatan	1,499.6	265.1	704.7	0.2	0.8	260.7	2,271.9	5,003.0
Sumatera Utara	660.9	116.8	310.6	7.8	4.2	217.0	116.9	1,434.2
Total	12,319.5	2,177.5	5,789.2	23.8	28.6	3,084.3	7,290.3	30,713.2

5. Pumped hydro energy storage technical potential

Another effort to solve the variability issue is providing storage from PHES technology in which its technology has a lifetime of 50 years (Ministry of Energy and Mineral Resources Republic Indonesia & Danish Energy Agency, 2021). By selecting further the location of PHES from Stocks et al. (2021, 2019) considering locations near the water bodies, outside residential and protected areas, and outside transportation routes, we find that the potential of PHES in Indonesia is 7308.8 GWh (detailed in Table 13 and 14).

Table 13. Detailed site numbers per province depending on storage capacity (total energy and hours)

Province	Number of sites depending on the total energy and storage time							
	2 GWh - 6 hours	5 GWh - 6 hours	5 GWh - 18 hours	15 GWh - 6 hours	15 GWh - 18 hours	50 GWh - 6 hours	50 GWh - 18 hours	150 GWh - 18 hours
Aceh	0	12	52	12	132	8	82	37
Bali	0	0	2	0	3	0	1	0
Banten	0	0	1	0	6	0	3	2
Bengkulu	0	0	3	0	13	0	5	4
DI Yogyakarta	0	0	0	0	1	0	0	0
DKI Jakarta	0	0	0	0	0	0	0	0
Gorontalo	0	0	0	0	4	0	1	1
Jambi	0	0	0	0	2	0	0	2
Jawa Barat	0	2	6	2	51	1	32	19
Jawa Tengah	0	0	5	0	24	1	14	10
Jawa Timur	0	1	14	1	32	1	22	10
Kalimantan Barat	0	3	14	4	45	6	35	17
Kalimantan Selatan	0	0	1	0	2	0	2	2
Kalimantan Tengah	0	1	8	3	20	3	11	7
Kalimantan Timur	0	4	30	2	89	1	64	29
Kalimantan Utara	0	3	10	3	39	2	30	10
Kepulauan Bangka Belitung	0	0	0	0	0	0	0	0
Kepulauan Riau	0	0	0	0	0	0	0	0
Lampung	0	0	1	0	10	0	6	4
Maluku	0	10	30	3	45	3	33	12
Maluku Utara	0	2	7	0	14	0	14	8
Nusa Tenggara Barat	0	0	0	0	7	0	1	0
Nusa Tenggara Timur	0	5	25	3	75	4	46	23
Papua	2	17	46	11	112	6	53	23
Papua Barat	0	20	42	8	54	5	23	6
Riau	0	0	0	0	0	0	0	0
Sulawesi Barat	0	8	22	9	61	6	34	16
Sulawesi Selatan	1	6	15	3	78	2	54	23
Sulawesi Tengah	0	21	85	16	184	9	106	47
Sulawesi Tenggara	0	10	20	6	42	6	34	12
Sulawesi Utara	0	0	0	0	0	0	0	0
Sumatera Barat	0	1	6	0	12	1	10	5
Sumatera Selatan	0	0	1	0	10	0	9	6
Sumatera Utara	0	4	25	3	95	4	59	30
Total sites	3	130	471	89	1,262	69	784	365

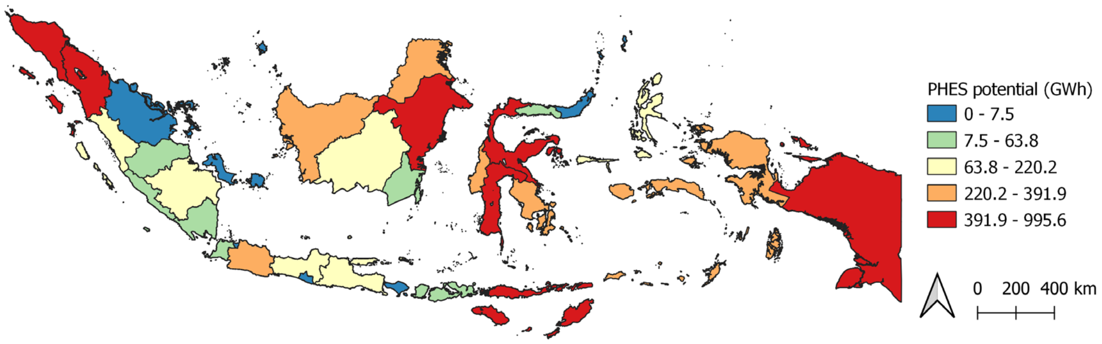


Figure 8. Technical energy potential of PHES grade A in Indonesia, originally done by Stocks et al. (2021, 2019) and furtherly filtered in this study to select the best location for installing PHES.

Table 14. Total generated power per hour per province

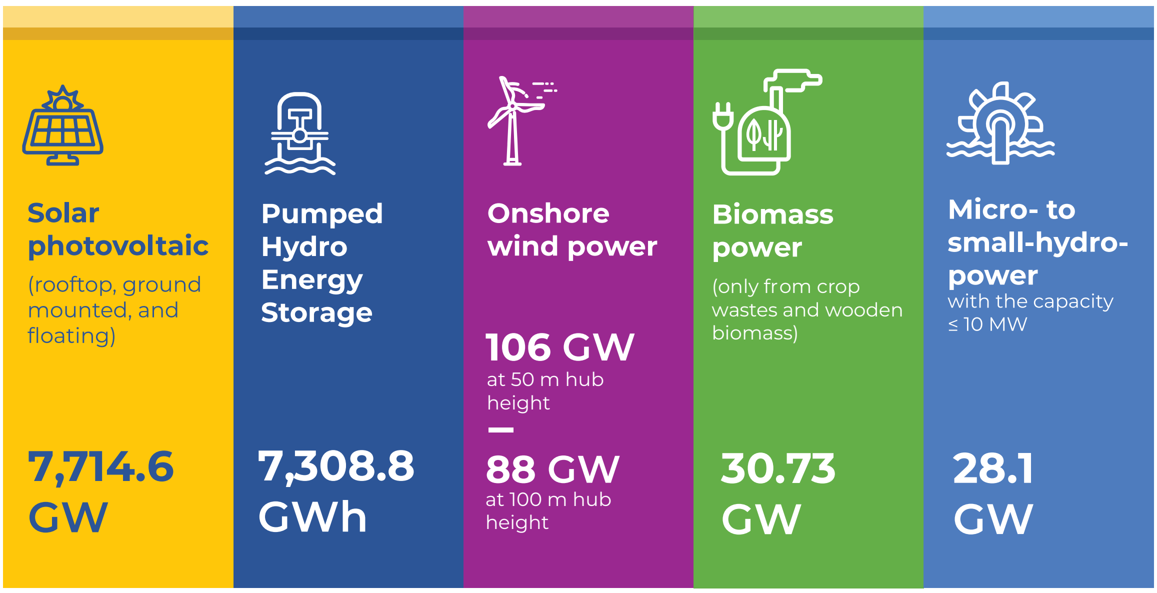
Province	Energy per hour (GWh)
Aceh	767.2
Bali	5.8
Banten	30.3
Bengkulu	58.9
DI Yogyakarta	0.8
DKI Jakarta	0.0
Gorontalo	14.4
Jambi	18.3
Jawa Barat	306.4
Jawa Tengah	151.9
Jawa Timur	186.7
Kalimantan Barat	342.8
Kalimantan Selatan	24.2
Kalimantan Tengah	141.1
Kalimantan Timur	518.6
Kalimantan Utara	228.6
Kepulauan Bangka Belitung	0.0
Kepulauan Riau	0.0
Lampung	58.6
Maluku	278.3
Maluku Utara	120.8
Nusa Tenggara Barat	8.6
Nusa Tenggara Timur	433.9
Papua	537.3
Papua Barat	248.9
Riau	0.0
Sulawesi Barat	363.9
Sulawesi Selatan	440.3
Sulawesi Tengah	995.6
Sulawesi Tenggara	308.3
Sulawesi Utara	0.0
Sumatera Barat	90.3
Sumatera Selatan	83.6
Sumatera Utara	544.2
Total	7,308.8

Conclusion and recommendations

Indonesia has an ample amount of renewable energy potential and this study successfully proves the possibility to take advantage of their sources to supply the power demand (Figure 9). Solar-, wind-, categorized as VREs depending highly to the weather conditions, and hydropower, has the potential up to 7,714.6 GW if there is no restriction in the surface coverage utilization, additionally 28.1 GW if we allow to build more than one micro to small hydropower plants in a tributary, and 106 GW if we use minimum 6 m/s of wind speed at 50 meters of onshore wind turbines. Even when we apply some restrictions to resource exploitation for the sake of ecosystem sustainability and robust production estimation, we can supply the power demand using 6,749.3 GW from solar power, 6.3 GW from micro- to small-hydropower, and 25 GW from onshore wind power.

Due to its high variability, we need to provide other resources to solve this issue. Empowering biomass power plants, whose feedstocks do not fluctuate hourly and daily, can be one of the solutions which can supply 188.4 GW according to the results of this study. However, the efficiency of biomass power plants is only 20-35% and we thus need another option to solve the variability issues. PHES, which is well-known as a natural battery, can also be the solution because it can be activated to solve the deficit supply from VREs. The potential of PHES grade A in Indonesia is 7,308.8 GWh.

Scenario 1



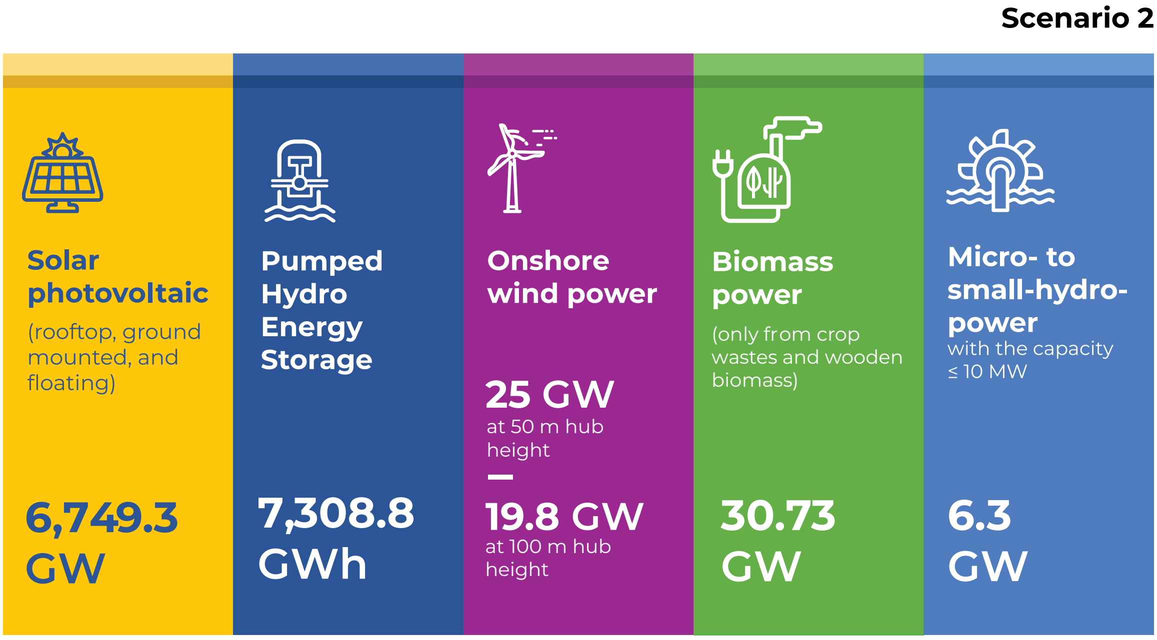


Figure 9. Total technical potential capacity per technology that can be applied in Indonesia based on two scenarios

Based on the findings, we recommend that:

1

The government updates Indonesia's renewable energy technical potential data and reviews them regularly as the technologies mature.

Thorough and comprehensive mapping of actual natural resources will show not only the abundant potential, but also the corresponding areas to develop and the subsequent potential renewables project pipelines.

2

The government and experts complement the map with updated data on intermittency, variability, and grid assessment, including the forecasted data.

Such comprehensive data is able to provide insights to stakeholders to produce a more robust project plan considering the impact of climate change and grid readiness on the opportunities to deploy renewable energy in Indonesia. Simulated weather conditions from several climate scenarios (e.g. ERA5, CIMP5, and weather generators) can be used to analyze changes in renewable energy potential due to future climate.

3

The government and stakeholders consider decentralized power system and connected islands

as two ways to provide the electricity powered by renewable energy to all islands since there are neglected renewable energy potentials outside Java (e.g. solar power potential in East Kalimantan and micro- to small-hydropower in Papua).

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