Beyond 207 Gigawatts: Unleashing Indonesia's Solar Potential

Nationwide solar potential assessment based on geographic information system (GIS) mapping

TECHNICAL PAPER

IMPRINT

Research team (in alphabetical order):
Agus Tampubolon
Daniel Kurniawan **(Lead Researcher and Author)**
Deon Arinaldo
Handriyanti Diah Puspitarini
Hapsari Damayanti
Idoan Marciano

Reviewers (in alphabetical order):
Fabby Tumiwa, IESR
Marlistya Citraningrum, IESR
Dr. Xu Shengnian, GEI

Please cite this report as:
IESR (2021). Beyond 207 Gigawatts: Unleashing Indonesia's Solar Potential . Institute for Essential Services Reform.

First publication:
March 2021

This report is supported by the Global Environmental Institute (GEI) of China. IESR is solely responsible for the content of this report.

Acknowledgement:
Several data used in this study are provided by Badan Informasi Geospasial (BIG), with support from Directorate of Various New and Renewable Energy of MEMR, Indonesia.

Executive Summary

Seeing the need for an update for solar power technical potential in Indonesia, the Institute for Essential Services Reform (IESR), with technical support from the Global Environmental Institute (GEI), conducted a nationwide geographic information system-based (GIS-based) solar photovoltaics (PV) technical potential assessment in the country.

Technical potential estimates represent the achievable electricity generation potential (terawatt-hours), including its capacity potential (gigawatt-peak) and suitable land area (square kilometers), given the topographical (geographical) and land-use constraints as well as PV system performance. Technical potential is different with economic or market potential, as it does not consider projected costs and policy and regulatory limits (other than those related to land-use), and thus, do not represent the level of generation that might actually be deployed, but rather an upper-boundary estimate of development potential. Using publicly available GIS data, this report covers both national- and provincial-level results of Indonesia's spatial analysis and focuses on large-scale (utility-scale) ground mounted solar PV application.

The analysis of this report is the first step of a series of activities to assess potential solar PV projects in Indonesia and provides an overview of national solar power potential before zooming in to the potential regions. The estimation of the technical potential starts with first assessing the suitable areas and terrain for solar PV development. Then, by considering the solar resource potential in the areas and taking some technology-specific assumptions, the technical potential can be calculated. Several constraints to determine the suitable areas include certain terrain features (e.g., ground slope), protected areas, land-use restriction, water bodies, and others. Table ES-1 presents the solar PV technical potential in Indonesia, given several land-use restriction scenarios.

Table ES-1. Summary of Indonesia's solar PV technical potential assessment

Scenarios	Suitable area (km^2) *(% of Indonesia's total land mass)*	Solar PV Technical Potential	
		Capacity (GWp)	Generation (TWh/year)
Scenario 1 (S1): Base exclusions (protected areas, forested areas, water bodies, wetland areas, airports and seaports) + slope exclusion (>10°)	484,455 *(24.43%)*	19,835	26,972
Scenario 2 (S2): S1 + agricultural lands (both pure and shrub-mixed) and plantation forest areas exclusions	187,806 *(9.85%)*	7,700	10,508
Scenario 3 (S3): S2 + transmigration and settlements areas exclusions	153,915 *(8.07%)*	6,310	8,541
Scenario 4 (S4): S2 + dry shrub exclusion	82,847 *(4.34%)*	3,397	4,705

Based on the findings of the assessment, Indonesia's solar PV technical potential range between 16 to 95 times larger compared to the current national estimates by the Ministry of Energy and Mineral Resources (MEMR), that is 207 GW.

As the assessment goes into provincial and cities/regencies level, the findings can be used to inform policymakers, PLN, business players, and other relevant stakeholders to accelerate solar development in Indonesia, starting by updating Indonesia's solar potential figure and identifying potential solar projects across the country.

Table of Contents

Lombok Solar Project
Photo: Vena Energy

1 Introduction

1.1 Background

Indonesia, through its National Energy Policy (*Kebijakan Energi Nasional*, KEN) set in 2014, has set a policy target to increase its renewable energy share in its primary energy mix to 23% in 2025 and to 31% by 2050. This is further translated into the National Energy General Plan (*Rencana Umum Energi Nasional*, RUEN) in 2017, where renewables-based power installed capacity is targeted to be 45 GW (or 33% of total projected installed capacity) in 2025, although this number is already outdated, as the macroeconomic assumptions are no longer relevant (overly optimistic) to the actual macroeconomic status (IESR, 2020). Under RUEN, the Indonesian government targets 6.5 GW of solar power installed capacity (out of the 45 GW) by 2025. However, by the end of 2020, the Institute for Essential Services Reform (IESR) recorded that solar PV installed capacity only reached 181.2 MW (IESR, 2021).

When it comes to the technical potential for renewable energy (for power generation), solar power is regarded as the largest resource by the Indonesian government, totaling 207 GW, according to the Ministry of Energy and Mineral Resources (MEMR) (MEMR, 2016). However, after comparing the technical potential with other countries such as the United States, we found that the current Indonesia's solar technical potential is way too low for a country with a total land mass of 1.9 million square kilometers. In comparison, the National Renewable Energy Laboratory (NREL) found that solar PV technical potential in the United States totals a maximum of 152,974 GW for rural utility-scale solar PV, amounting to 3 million square kilometers of suitable land area (or 32% of the U.S. total land mass of 9.8 million square kilometers) (NREL, 2012). As Indonesian government is now considering a renewable energy grand strategy prioritizing solar energy, there is a need to thoroughly map and update solar power technical potential in the country. Against this backdrop, and in order to support solar power development in the country, IESR, with technical support from the Global Environmental Institute (GEI), conducted a geographic information system-based (GIS-based) solar PV technical potential assessment in Indonesia.

1.2 Renewable Energy Potential Definitions

When discussing renewable energy potential, it is useful to understand the difference between several terminologies related to potential, such as resource potential, technical potential, economic potential, and market potential (see **Figure 1**). In this report, technical potential is considered as opposed to economic or market potential. Technical potential represents the achievable electricity generation potential (terawatt-hours, TWh), including its capacity potential (gigawatt-peak, GWp) and suitable land area (square kilometers, km2), given the topographical (geographical) and land-use constraints as well as PV system performance. Technical potential is different with economic or market potential, as it does not consider projected costs and policy and regulatory limits (other than those related to land-use), and thus, do not represent the level of generation that might actually be deployed, but rather an upper-boundary estimate of development potential.

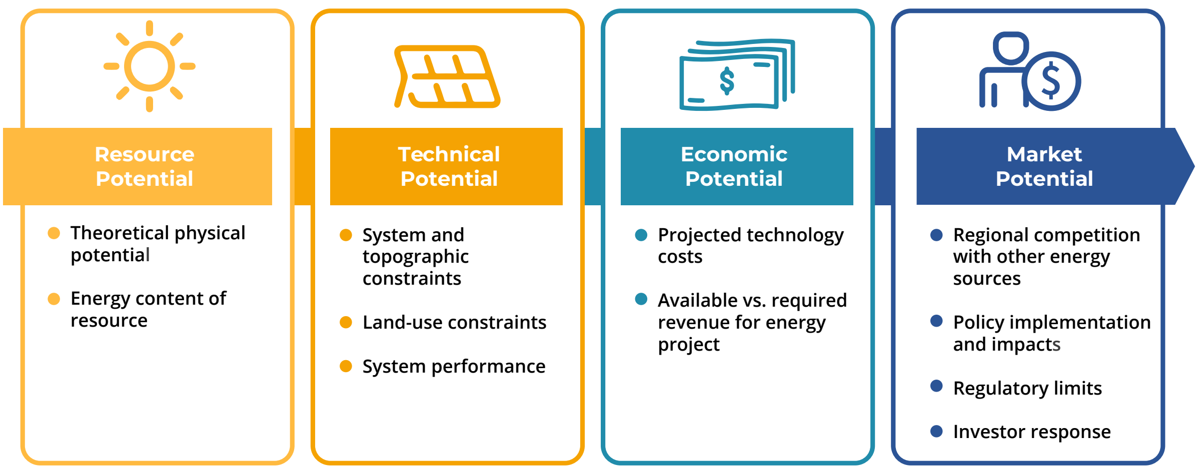

Figure 1. Types of Renewable Energy Generation Potential. Adapted from NREL (2016)

1.3 Scope of Analysis

This report uses a geospatial analysis method to estimate the technical potential of solar energy using photovoltaic (PV) technology in Indonesia. More specifically, the assessment focuses on the application of ground-mounted utility-scale solar PV across the country. Current assessment excludes other solar PV applications such as rooftop PV and floating PV, as it does not consider roof space specifically and water bodies, respectively. For a nationwide rooftop PV technical potential, one can refer to another study conducted by IESR (2019a).

This report covers both national and provincial-level results of Indonesia's spatial analysis, estimating the suitable land area (in square kilometers), technical potential capacity (in gigawatts), and technical potential generation (in terawatt-hours), as presented in Section 3. The analysis is the first step of a series of activities to assess potential solar projects in Indonesia and provides an overview of national solar power potential before zooming in to the potential regions.

The estimation of technical potential for power generation starts with first assessing the suitable areas and terrain for solar PV development. Then, by considering the solar resource potential in the areas and taking some technology-specific assumptions, the technical potential could be calculated. Several constraints to determine the suitable areas include certain terrain features (e.g., ground slope), protected areas, land-use restriction, water bodies, and others. Figure 2 displays the graphical representation of technical potential by a series of land-use exclusions.

Performing the assessment, a spatial analysis tool is utilized. This tool helps to map and estimate the outputs as described above by processing data input layers separately, to do analysis and estimation for each layer and to further stack them to generate the final output. The more detailed methodology is outlined in the section below. All the data inputs and assumptions used in this analysis, including power density, capacity factors, land-use constraints, and others were sourced from published research, publicly available GIS data, i.e., government and international open-source databases, such as data from Geospatial Information Agency (*Badan Informasi Geospasial*, "BIG"), Ministry of Environment and Forestry, and UNEP's World Database of Protected Areas (see Table 2 in Section 2 for more details), expert judgements, and analysis by IESR and GEI.

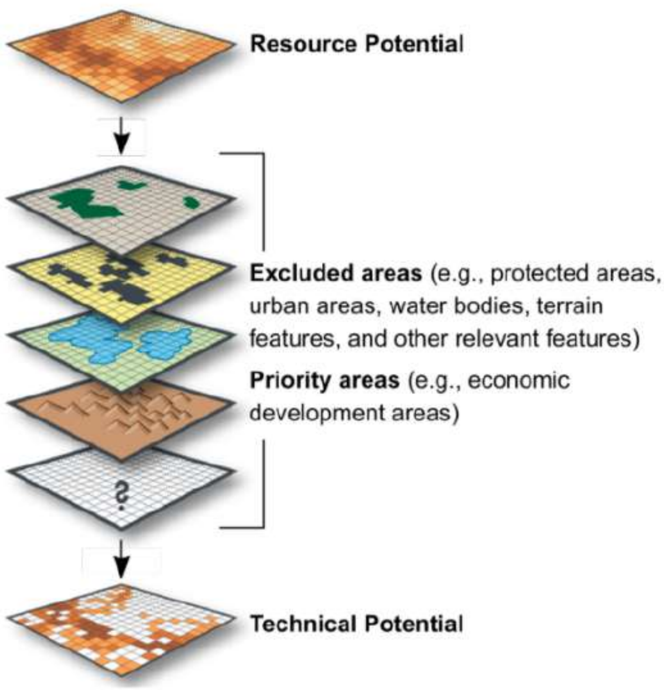

Figure 2. Graphical representation of technical potential. Adapted from USAID & NREL (2017)

2 Methods

This section describes the methodology used to estimate the technical potential of solar power across the country. The analysis includes considerations of different exclusion layers to identify the suitable land areas for solar power development, then, by finding the total area and using several technology-specific assumptions, solar power technical potential is determined. Since the estimation is strongly related to the performance characteristics of the solar power technology considered, the numbers will likely change parallel to the evolution of the technology.

The results of the analysis are presented in the form of maps, showing the suitable areas for solar PV development and different ranges of solar PV technical potentials across different provinces and districts in Indonesia. The main steps of the analysis along with the geographic considerations and assumptions used are further described below.

2.1 Methodology

A GIS-based approach is used to assess the solar power technical potential. Specifically, the analysis is done within QGIS (https://www.qgis.org/en/site/), a free and open-source GIS application, utilizing multiple geographic data layers including the digital elevation model (DEM) data, administrative boundaries, land cover, and protected areas, and solar PV power output (PVOUT) across Indonesia. In general, the steps to map the suitable areas and solar PV technical potential are as follows

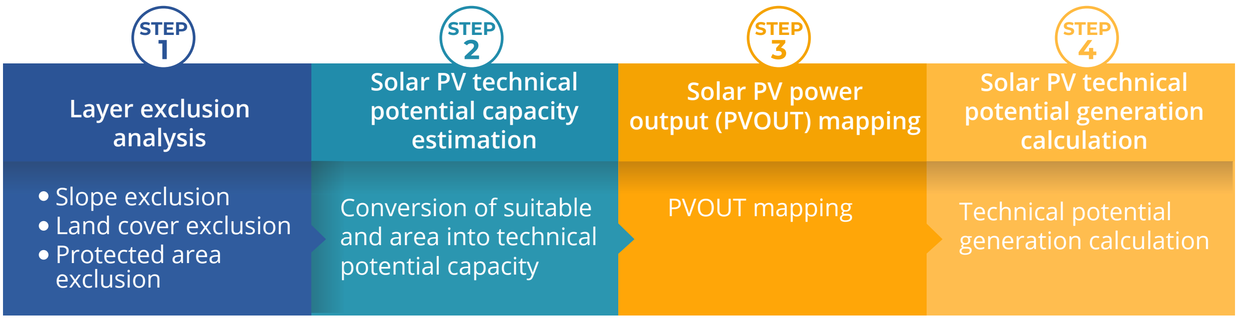

Figure 3. Solar PV technical potential calculation methods employed in this assessment

Step 1. Layer exclusion analysis. This step aims to map the suitable land areas for solar PV development. This is done by layering one map with another, each containing information of geographic constraints, such as slope limitation, land-use restriction, and protected areas. Therefore, the land areas that are deemed not technically developable could be filtered out, leaving the suitable land areas to be shown.

First, the **topographic map** of each province in Indonesia in the form of **DEM files** are imported to QGIS. Then for these raster files, **a slope limit of 10°** (17.6% in percent slope) is set, thus separating areas within and beyond the limit set. They are then clipped with the administrative boundaries map for each province and converted into vector files to be layered with land cover, protected areas and solar PV capacity factor map afterwards. The vectorized geometries are checked and fixed to remove any errors that might hinder subsequent analysis. From this step, the output is a vectorized map of each province showing areas within and beyond the slope limit of 10°.

Separately, the **land cover** dataset is processed to show selected land-use areas available for each province. The national land cover map is clipped by the administrative boundaries map for each province, and then the land-use areas chosen are identified and selected to filter out other land-use areas deemed unsuitable. The resulting geometries are checked and fixed to remove any errors. The output of this process is then intersected with vectorized DEM files.

Finally, the **protected areas** map is also clipped by the administrative boundaries map for each province, and then checked and fixed to remove geometry errors. Finally, the protected areas layer is crossed with the intersection result of land cover and DEM layers using the "difference" function to remove the protected areas from the end result of the suitable areas map. The output of this step is the map of suitable areas for solar PV development in each province of Indonesia.

Step 2. Solar PV technical potential capacity estimation. The total technical potential for electricity generation (GWp) is calculated for each district and province; and is also aggregated to show results for the entire country. The technical potential capacity equation is given as follows:

$$\textit{Technical potential capacity (GWp)} = \textit{Land Area } (km^2) \times \textit{Power Density } (GWp/km^2)$$

The total land area (km^2) for each district and province is obtained from QGIS results of suitable areas from the first step. On the other hand, the **power density** of solar PV varies based on the technologies available. The power density implies the maximum power that solar PV could produce for a unit area of land, with specific assumptions for each technology. A rather conservative assumption was chosen, based on utility-scale solar PV technologies installed in the United States (NREL, 2013). According to the publication, the land requirement for fixed-tilt solar PV technologies is around 7.6 acres/MWac (or 0.33 MWac/hectare). Taking into account DC/AC ratio of 1.25, a power density of **0.41 MWp/hectare (0.041 GWp/km²)** is obtained and used for the analysis. It is important to note that power density in more recent projects in Indonesia can range between 0.6–0.8 MWp/hectare, as seen in Likupang 21 MWp and Lombok 3 x 7 MWp solar projects that use ~16% efficient solar module (ADB, 2018a, 2018b). Hence, a higher technical potential estimate can still be obtained.

Step 3. Solar PV power output mapping. In order to calculate the technical potential generation (TWh/year) for each region, solar PV power output (PVOUT) needs to first be assigned to the suitable land areas layers. The PVOUT map provides a summary of estimated solar photovoltaic (PV) power generation potential as a long-term average of yearly (or daily) potential of electricity production from a 1 kWp solar PV power plant (in other words, its capacity factor). The $PVOUT_{daily}$ data were used and obtained from SolarGIS (http://solargis.info), which are given in the unit of kWh/kWp/day for regions across Indonesia. The PVOUT data is imported to QGIS and then clipped with the administrative boundaries map for each province. Then, the geometries are checked and fixed to remove any errors.

Step 4. Solar PV technical potential generation calculation. The annual technical potential generation of solar PV (in TWh/year) is then calculated with an additional factor of capacity factor determined in the step above. The equation used to estimate the technical potential generation is as follows.

$$\textit{Technical potential generation (TWh/year)} = \textit{Land Area } (km^2) \times \textit{Power Density } (GWp/km^2) \times PVOUT_{daily} (GWh/GWp)/day \times 365\ days/year \times 1/1000\ (TWh/GWh)$$

This equation is applied in QGIS for each province and then the technical potential generation for each district is shown in a range of values. This is done by classifying the technical potential generation based on quantiles, meaning that each range of values (class) contains an equal number of regions. This classification method is chosen over equal-interval classification to avoid skewness towards a certain range of values. Similarly, the technical potential generation is also presented in national scale, aggregating total technical generation potential for each province and showing it in the form of a range of values.

2.2 Geographic Constraints

Multiple geographic constraints are considered to determine the suitable areas for solar PV development, namely: ground slope, land-use restrictions, and protected areas. Steep terrain presents a limiting factor to the installation of large-scale solar PV. Several rules of thumbs of the optimal ground slope for solar PV development are available, an optimistic number was chosen: a ground **slope of less than 10º** (17.6% in percent slope) as the limit.

Land-use restrictions refer to the areas which are deemed applicable for solar PV installation, thus excluding those that are unsuitable due to its purpose. In general, **forest areas, water bodies, and wetlands** are excluded as restricted land use from analysis. While there is a possibility to include floating solar PV in the calculation, we decided not to include it in this assessment as detailed in Section 1.3. Furthermore, **agricultural lands** that are considered essential for food production are also excluded (e.g., rice fields, estate crops plantations, fishponds). **Airports and seaports** are also not considered due to limited space available for solar PV installation. The complete list of land-use areas chosen in this analysis is shown by **Table 1**.

Those selected land-use areas do not include protected areas, which are also kept out of this analysis. Protected area constraints include nationally protected lands and areas of critical environmental or biodiversity concern. Referring to IUCN (International Union for Conservation of Nature) definition of a protected area: “a protected area is a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, to achieve the long term conservation of nature with associated ecosystem services and cultural values” (UNEP-WCMC & IUCN, 2016). This analysis takes the data from the World Database of Protected Areas, which is developed by the UN Environment Programme (UNEP) and the IUCN. In Indonesia, the protected areas list includes national parks, nature reserves, wildlife reserves, recreation parks and others.

Table 1. Land cover types suitable for solar PV development in Indonesia

No.	Land Cover Type	Category[1]	Description[2]
1	Plantation forest	Plantation forest	Forests that have been grown in dry land habitats by human intervention
2	Shrub	Grassland	Dry land overgrown with various types of heterogeneous natural vegetation with rare to dense density levels and dominated by low vegetation Notes: in Indonesia, grove is usually former forest areas and usually does not re-show cut marks or spots.
3	Savannah	Grassland	Open areas dominated by various types of grass and trees that grow spread out and sparsely
4	Dry agricultural land	Cropland	Areas used for cultivation of single-type crops; between planting periods, this area is usually not covered with vegetation
5	Shrub-mixed dry agricultural land	Cropland	Areas used for cultivation of more than one type of crops; between planting periods, this area is usually not covered with vegetation
6	Bare land	Other land	Land without cover, whether natural, semi-natural or artificial
7	Mining area	Other land	Open land as a result of mining activities
8	Settlement area	Settlement	Areas used as residential or residential environment and a place for activities that support people's lives
9	Transmigration area	Settlement	Transmigration areas including general (government-sponsored, centralized), spontaneous, and local transmigration areas

Note: For a complete list of land cover classification by the Ministry of Environment and Forestry (MoEF), please refer to Appendix A

All the sources for the geographic constraints' layers used within QGIS are compiled in the **Table 2** below.

[1]Reclassified by World Resources Institute (Global Forest Watch, 2020)

[2]Obtained from Indonesian National Standard (SNI) on land cover classification (BSN, 2010)

Table 2. Geographic Constraints Datasets Sources Compilation

Data Type	Source	Description
Administrative boundaries (district level)	Geospatial Information Agency (2018)	This data is a representation of geospatial data of Indonesia, which includes district boundaries
Administrative boundaries (provincial level)	Directorate General of Population and Civil Registration, Ministry of Home Affairs (2020)	This data shows province boundaries across Indonesia, compiled by Directorate General of Population and Civil Registration.
Digital Elevation Model (DEM)	Geospatial Information Agency (2018)	National DEM of Indonesia is a topographic data, built from different sources, namely IFSAR (5 m resolution), TERRASAR-X (5 m resolution) and ALOS PALSAR (11.25 m resolution) and mass point data resulting from stereo-plotting. The resolution of this DEM is 0.27 arc-second (roughly 8 m)
Land cover data[3]	Ministry of Environment and Forestry (2017)	This data shows 2017 Indonesia land cover, classified by type (1:250,000 scale). The World Resources Institute reclassified the original land cover categories from the Ministry of Environment & Forestry dataset into the following categories (Global Forest Watch, 2020): • Primary Forest: Primary dry land forest, primary mangrove forest, primary swamp forest • Secondary Forest: Secondary dryland forest, secondary mangrove forest, secondary swamp forest • Plantation Forest: Plantation forest • Grassland: Bush/Shrub, Savannah • Cropland: Estate crop plantation, dryland agriculture, shrub-mixed dryland farm, rice field • Other Land: Bare land, fish pond, airport/ harbor, mining area • Settlement: Transmigration area, settlement area • Wetland: Swamp, swamp shrub • Unknown: Cloud • Bodies of Water: Bodies of water
Protected areas	UNEP's World Database of Protected Areas (2020)	This is a global database presenting marine and terrestrial protected areas, which is updated monthly. Datasets for Indonesia are taken from this database

[3]For a detailed list of land cover classification by the MoEF, please refer to Appendix A

Lastly, in order to understand the technical potential assessment results better, a set of scenarios on the land cover exclusions are included (see **Table 3**). **Scenario 1** features the most optimistic scenario where all land cover types listed in Table 1 are included. **Scenario 2**, on the other hand, selectively excludes agricultural lands (i.e., pure dry and shrub-mixed dry agricultural lands) and plantation forest, on the basis that both might be used for food production, and therefore not suitable for solar PV development. In Scenario 1, plantation forest and agricultural lands are included because the land are acquirable through land acquisition as previously seen in the 3 x 7 MWp ground-mounted solar projects in Lombok, East Nusa Tenggara and 21 MWp ground-mounted solar farm in Likupang, North Sulawesi (ADB, 2018a, 2018b). **Scenario 3** further excludes land cover types from settlement categories (transmigration and settlements) to focus on finding the suitable land outside populated areas. Lastly, **Scenario 4** excludes dry shrub to find a conservative estimate of the technical potential as dry shrub accounts for the majority of the land cover type.

Table 3. Summary of slope and land cover exclusions scenarios

Exclusions	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	Slope exclusion + natural forest, water bodies, wetland areas, airports and seaports + protected areas	Scenario 1 + agricultural areas and plantation forest exclusions	Scenario 2 + settlement areas exclusions (transmigration and settlements)	Scenario 2 + dry shrub exclusion
Slope				
Greater than 10°				
Land cover				
Natural forest				
Plantation forest				
Water bodies				
Wetland areas				
Agricultural lands				
Airports & seaports				
Settlement areas:				
- Transmigration				
- Settlements				
Dry shrub				
Protected areas				
Protected areas				

3 Results

This section presents the summary of the results of the nationwide GIS-based technical potential assessment for solar PV power generation in Indonesia. The results are presented both in a summary table of results and in geographic maps as outputs from QGIS analysis, first showing the nationwide suitable areas and then the technical generation potential per province. The results for each scenario are presented in Section 3.1.1 to Section 3.1.4.

3.1 Nationwide solar PV technical potential

Table 4 presents the summary results for Indonesia's solar PV technical potential for each scenario listed in Section 2.2. The table shows the summary of total suitable area for ground-mounted utility-scale solar PV development (in km^2) as well as its percentage relative to Indonesia's total land mass, technical potential capacity (in GWp), and its technical potential electricity generation (in TWh/year).

Table 4. Summary of Indonesia's solar PV technical potential assessment

Scenarios	Suitable area (km^2) *(% of Indonesia's total land mass)*	Solar PV Technical Potential	
		Capacity (GWp)	Generation (TWh/year)
Scenario 1 (S1): Base exclusions (protected areas, forested areas, water bodies, wetland areas, airports and seaports) + slope exclusion (>10°)	484,455 *(24.43%)*	19,835	26,972
Scenario 2 (S2): S1 + agricultural lands (both pure and shrub-mixed) and plantation forest areas exclusions	187,806 *(9.85%)*	7,700	10,508
Scenario 3 (S3): S2 + transmigration and settlements areas exclusions	153,915 *(8.07%)*	6,310	8,541
Scenario 4 (S4): S2 + dry shrub exclusion	82,847 *(4.34%)*	3,397	4,705

Notes: Scenario 1 includes dry shrub, savanna, bare land, mining, transmigration, settlements, plantation forests, pure dry and mixed agricultural lands; Scenario 2 excludes plantation forests, pure dry and mixed agricultural lands from Scenario 1; Scenario 3 excludes transmigration and settlements from Scenario 2; and Scenario 4 excludes dry shrub from Scenario 2;

The suitable area map features geographic constraints outlined in Section 2.2. The green color code represents the areas deemed suitable for solar PV development. The dark brown color represents areas with ground slope of more than 10° in the suitable land use areas, therefore, it is considered as unsuitable in this analysis. However, with appropriate technology application, those areas could be explored for solar PV installations. Areas shown by white and red-line color code are marked as unsuitable, due to their land use type and inclusion to protected areas listed by the UN Environment and IUCN.

The generation potential map shows the electricity generation (in terawatt-hour per year) of each province given the potential capacity and estimated annual production from solar irradiation or capacity factor estimation mentioned in Section 2.1. As can be seen in the figure, it shows a gradient of red showing its relative PV generation potential in each province (the darker the color means more potential generation).

3.1.1 Scenario 1

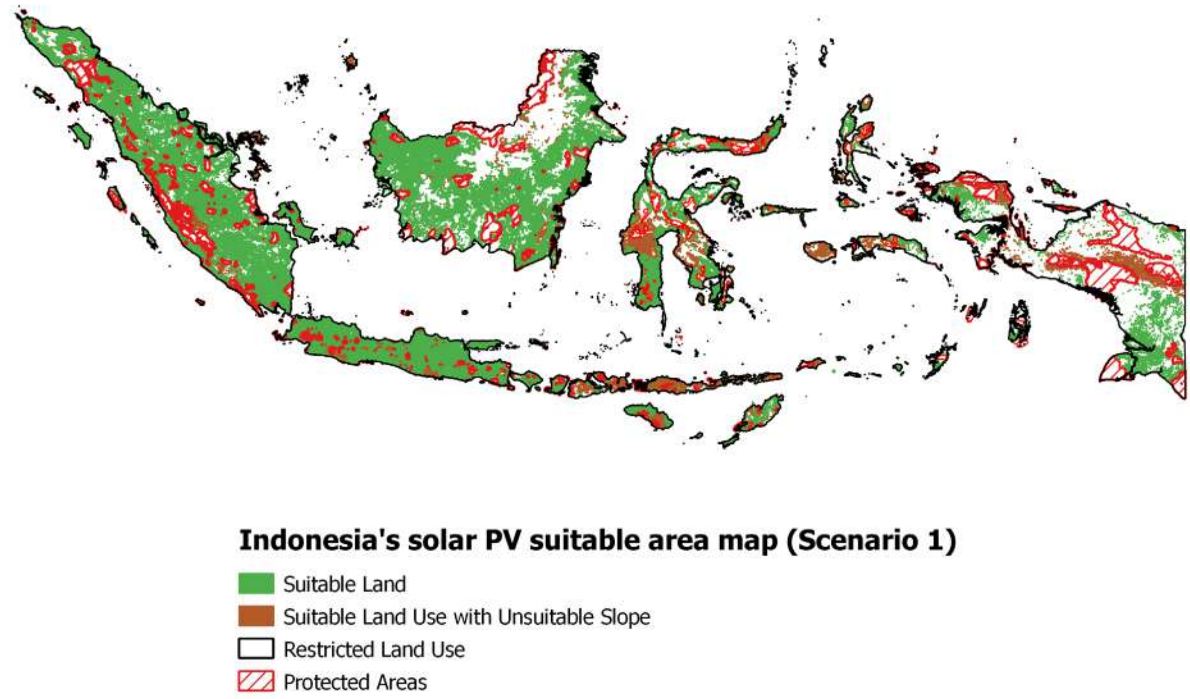

Figure 4. Indonesia's nationwide suitable area map for solar PV development (Scenario 1)

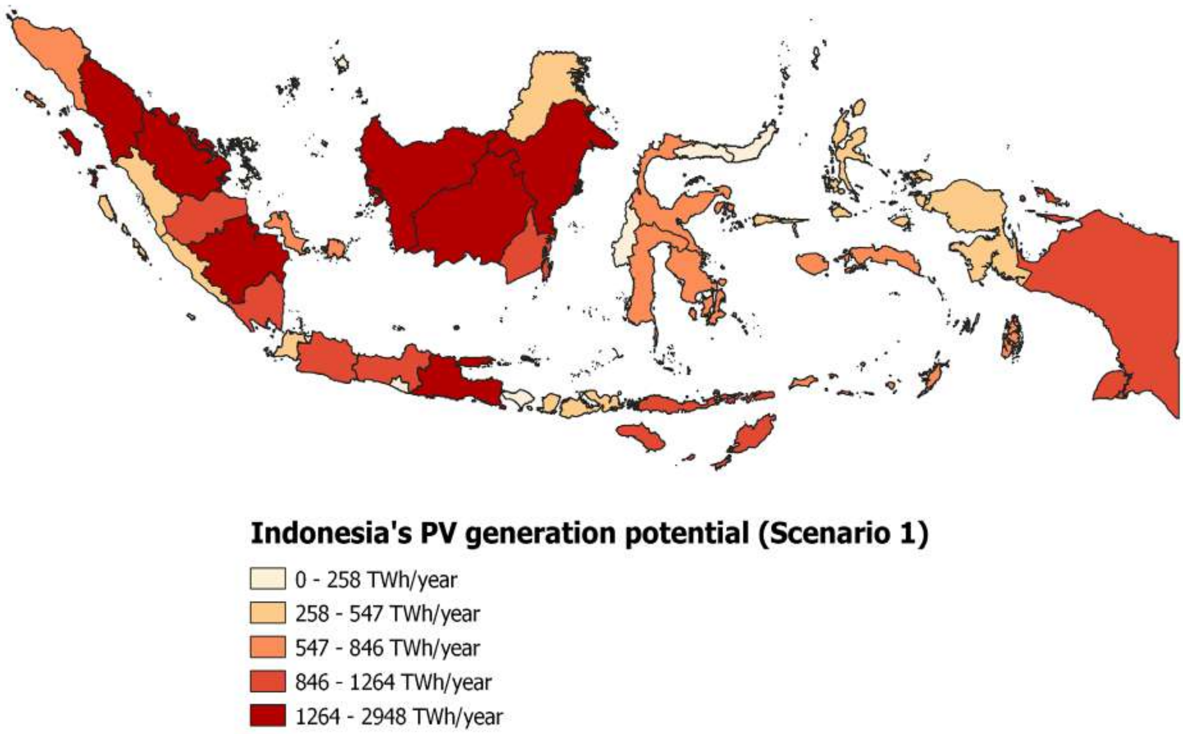

Figure 5. Indonesia's nationwide solar PV generation potential map (Scenario 1)

Table 5. Summary of solar PV technical potential in Indonesia (Scenario 1)

No	Province	Suitable Area (km²)	Capacity Potential (GWp)	Generation Potential (TWh/year)
1	Aceh	10,657	437	603
2	Sumatera Utara	27,625	1,133	1,509
3	Sumatera Barat	9,809	402	540
4	Riau	29,221	1,198	1,557
5	Jambi	22,574	926	1,198
6	Sumatera Selatan	27,213	1,116	1,495
7	Bengkulu	7,918	325	453
8	Lampung	16,464	675	909
9	Kepulauan Bangka Belitung	11,269	462	604
10	Kepulauan Riau	1,156	47	63
11	DKI Jakarta	593	24	33
12	Jawa Barat	16,746	687	946
13	Jawa Tengah	16,325	669	960
14	DI Yogyakarta	2,296	94	139
15	Jawa Timur	22,168	909	1,362
16	Banten	4,872	200	266
17	Bali	3,453	142	0.21
18	Nusa Tenggara Barat	4,759	195	309
19	Nusa Tenggara Timur	15,424	632	1,025
20	Kalimantan Barat	53,732	2,203	2,948
21	Kalimantan Tengah	34,435	1,412	1,877
22	Kalimantan Selatan	15,843	650	851
23	Kalimantan Timur	39,205	1,607	2,096
24	Kalimantan Utara	5,588	229	311
25	Sulawesi Utara	4,168	169	247
26	Sulawesi Tengah	10,626	430	619
27	Sulawesi Selatan	13,798	559	826
28	Sulawesi Tenggara	11,081	452	647
29	Gorontalo	2,376	96	146
30	Sulawesi Barat	2,859	114	168
31	Maluku	9,823	399	573
32	Maluku Utara	7,899	322	464
33	Papua Barat	4,874	200	274
34	Papua	17,607	722	955
	Total	**484,455**	**19,835**	**26,972**

Note: The provinces are arranged based on official numbering by the Ministry of Home Affairs (MoHA, 2017) (see Appendix A for more details).

3.1.2 Scenario 2

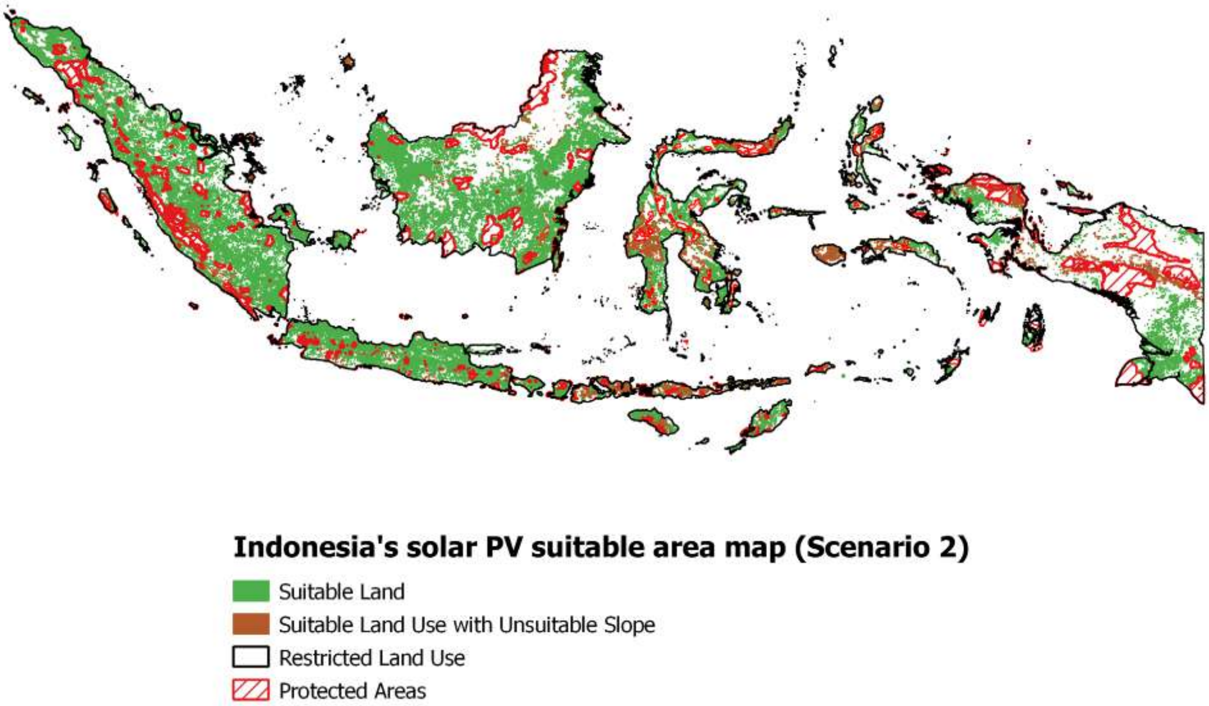

Figure 6. Indonesia's nationwide suitable area map for solar PV development (Scenario 2)

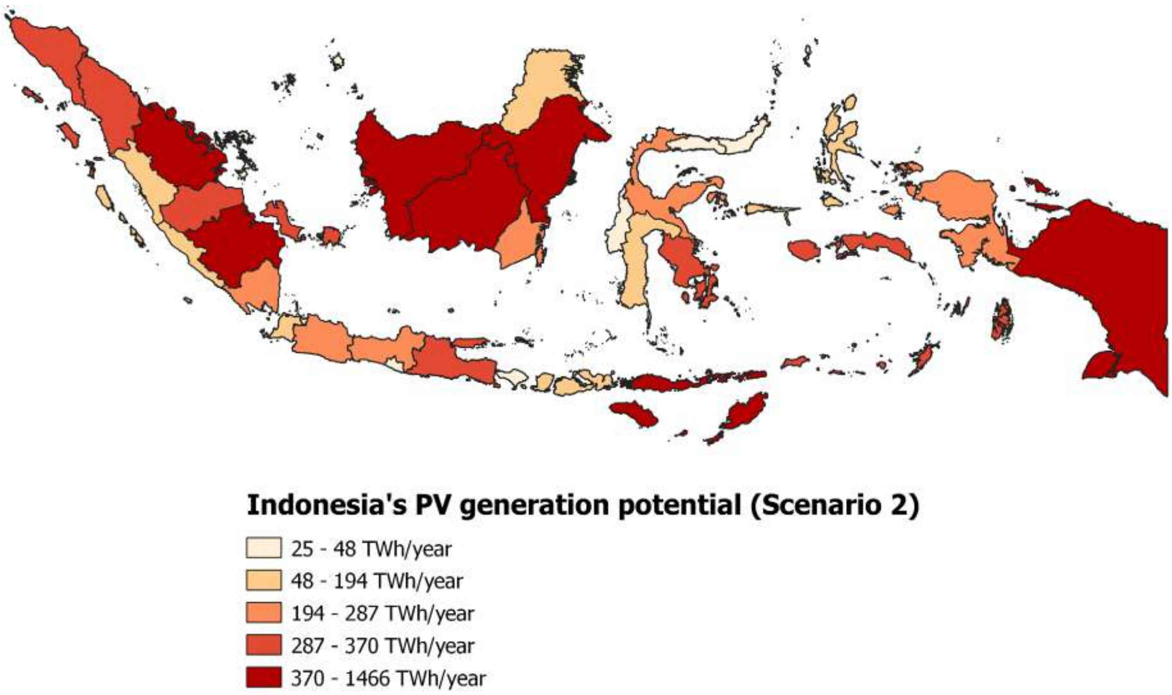

Figure 7. Indonesia's nationwide solar PV generation potential map (Scenario 2)

Table 6. Summary of solar PV technical potential in Indonesia (Scenario 2)

No	Province	Suitable Area (km^2)	Capacity Potential (GWp)	Generation Potential (TWh/year)
1	Aceh	5,293	217	300
2	Sumatera Utara	5,786	237	317
3	Sumatera Barat	2,059	84	113
4	Riau	7,267	298	386
5	Jambi	6,744	276	358
6	Sumatera Selatan	10,760	441	589
7	Bengkulu	1,570	64	91
8	Lampung	3,495	143	194
9	Kepulauan Bangka Belitung	5,343	219	287
10	Kepulauan Riau	622	25	34
11	DKI Jakarta	571	23	32
12	Jawa Barat	3,453	142	199
13	Jawa Tengah	4,699	193	284
14	DI Yogyakarta	680	28	41
15	Jawa Timur	4,876	200	306
16	Banten	948	39	52
17	Bali	644	26	41
18	Nusa Tenggara Barat	1,275	52	83
19	Nusa Tenggara Timur	8,258	339	552
20	Kalimantan Barat	24,360	999	1,343
21	Kalimantan Tengah	14,770	606	805
22	Kalimantan Selatan	5,116	210	274
23	Kalimantan Timur	27,330	1,121	1,466
24	Kalimantan Utara	3,481	143	194
25	Sulawesi Utara	507	21	30
26	Sulawesi Tengah	4,117	169	238
27	Sulawesi Selatan	2,588	106	153
28	Sulawesi Tenggara	5,023	206	294
29	Gorontalo	407	17	25
30	Sulawesi Barat	678	28	40
31	Maluku	4,960	203	289
32	Maluku Utara	2,069	85	120
33	Papua Barat	3,924	161	220
34	Papua	14,133	579	759
	Total	**187,806**	**7,700**	**10,508**

Note: The provinces are arranged based on official numbering by the Ministry of Home Affairs (MoHA, 2017) (see Appendix A for more details).

3.1.3 Scenario 3

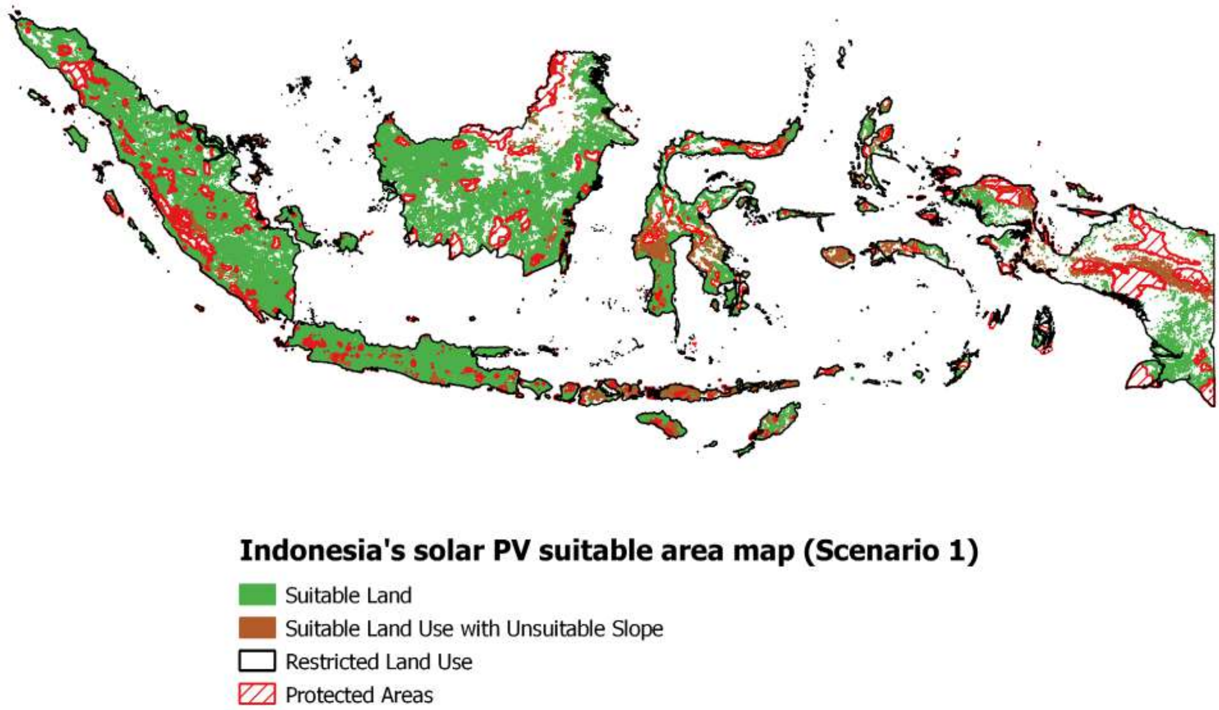

Figure 8. Indonesia's nationwide suitable area map for solar PV development (Scenario 3)

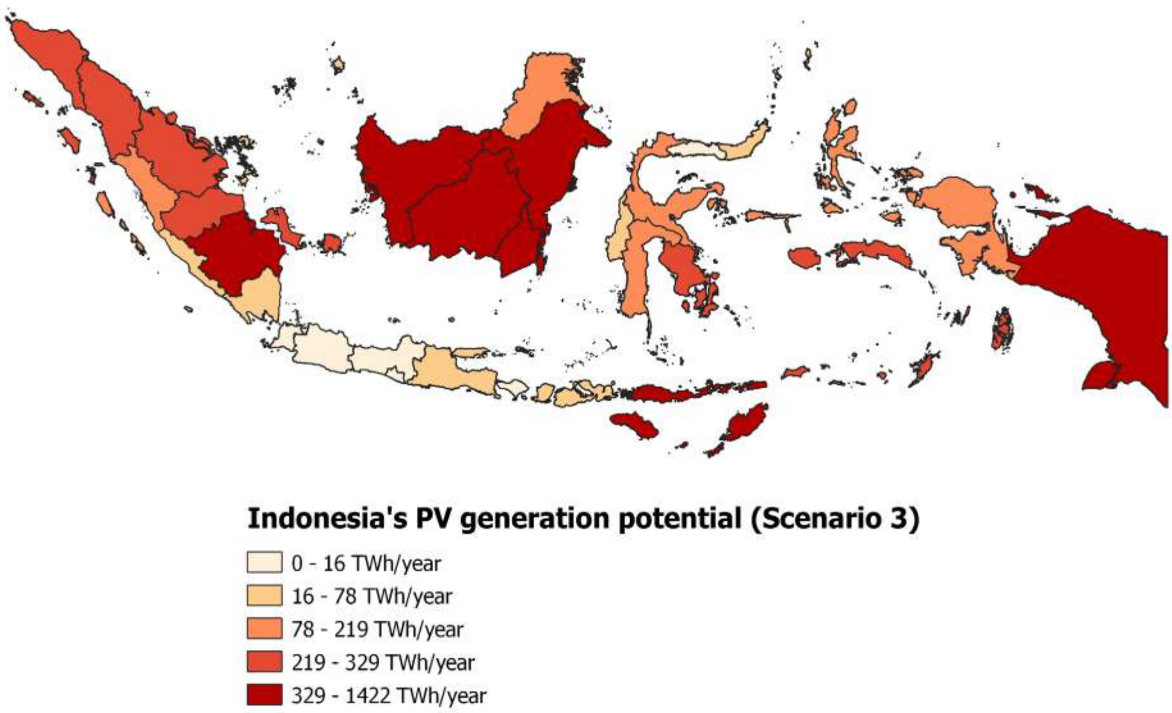

Figure 9. Indonesia's nationwide solar PV generation potential map (Scenario 3)

Table 7. Summary of solar PV technical potential in Indonesia (Scenario 3)

No	Province	Suitable Area (km²)	Capacity Potential (GWp)	Generation Potential (TWh/year)
1	Aceh	3,911	160	221
2	Sumatera Utara	4,980	204	273
3	Sumatera Barat	1,674	69	91
4	Riau	6,094	250	323
5	Jambi	5,627	231	299
6	Sumatera Selatan	8,490	348	464
7	Bengkulu	1,293	53	75
8	Lampung	879	36	49
9	Kepulauan Bangka Belitung	4,998	205	269
10	Kepulauan Riau	466	19	25
11	DKI Jakarta	0.67	0.03	0.04
12	Jawa Barat	93	4	5
13	Jawa Tengah	83	3	5
14	DI Yogyakarta	6.32	0.26	0.36
15	Jawa Timur	437	18	27
16	Banten	61	3	3
17	Bali	161	7	10
18	Nusa Tenggara Barat	896	37	59
19	Nusa Tenggara Timur	7,398	303	495
20	Kalimantan Barat	23,748	974	1,309
21	Kalimantan Tengah	13,958	572	760
22	Kalimantan Selatan	4,513	185	242
23	Kalimantan Timur	26,497	1,086	1,422
24	Kalimantan Utara	3,235	133	180
25	Sulawesi Utara	293	12	17
26	Sulawesi Tengah	3,659	150	211
27	Sulawesi Selatan	1,908	78	111
28	Sulawesi Tenggara	4,665	191	273
29	Gorontalo	261	11	16
30	Sulawesi Barat	470	19	27
31	Maluku	4,612	189	269
32	Maluku Utara	1,900	78	110
33	Papua Barat	3,432	141	192
34	Papua	13,213	542	707
	Total	**153,915**	**6,310**	**8,541**

Note: The provinces are arranged based on official numbering by the Ministry of Home Affairs (MoHA, 2017) (see Appendix A for more details).

3.1.4 Scenario 4

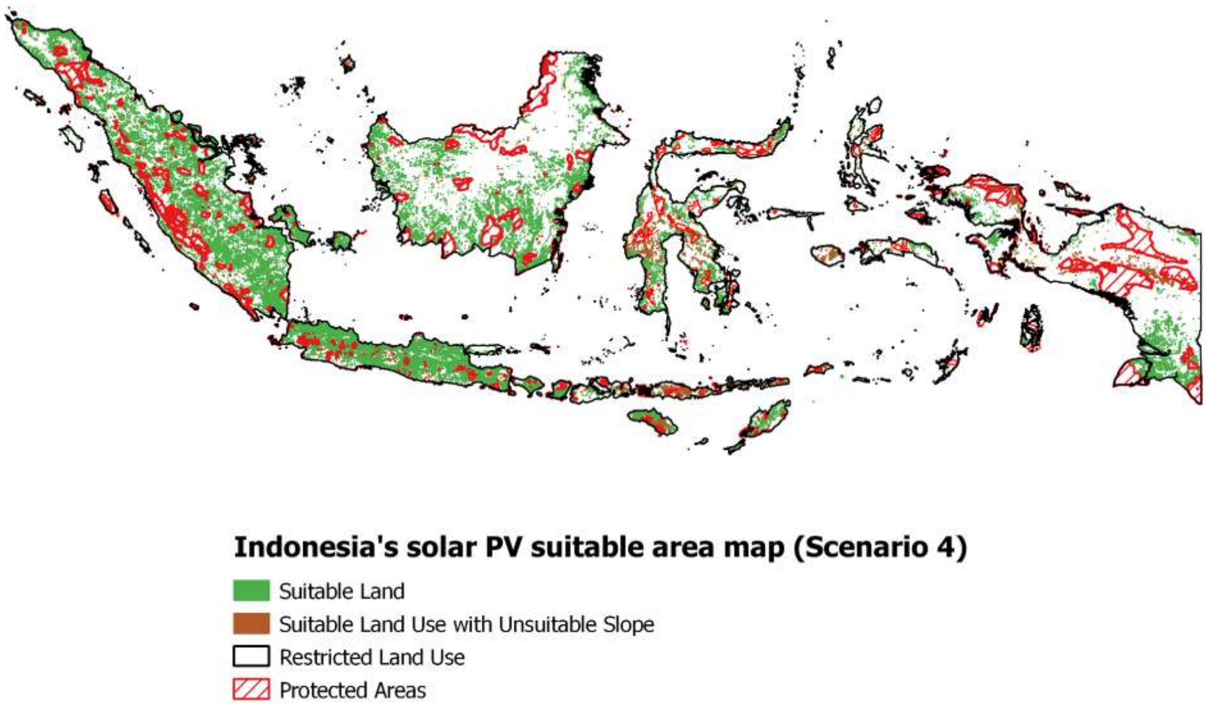

Figure 10. Indonesia's nationwide suitable area map for solar PV development (Scenario 4)

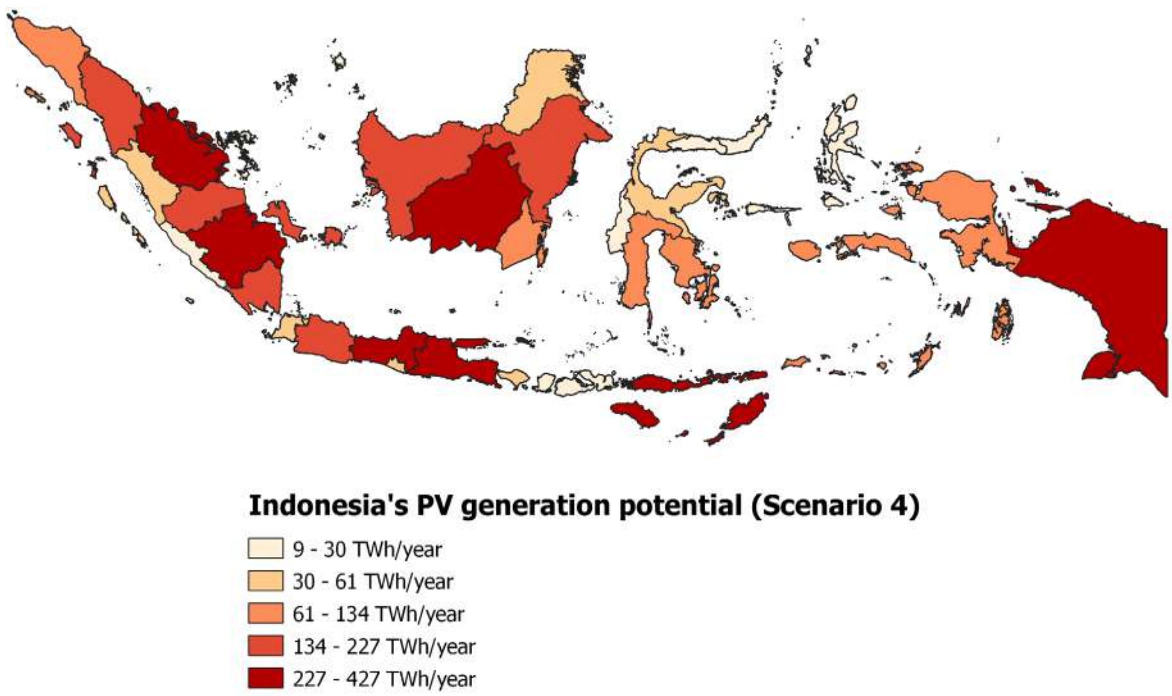

Figure 11. Indonesia's nationwide solar PV generation potential map (Scenario 4)

Table 8. Summary of solar PV technical potential in Indonesia (Scenario 4)

No	Province	Suitable Area (km^2)	Capacity Potential (GWp)	Generation Potential (TWh/year)
1	Aceh	2,094	86	120
2	Sumatera Utara	2,861	117	158
3	Sumatera Barat	873	36	49
4	Riau	7,059	289	375
5	Jambi	3,306	136	175
6	Sumatera Selatan	7,546	309	412
7	Bengkulu	371	15	22
8	Lampung	2,837	116	157
9	Kepulauan Bangka Belitung	2,546	104	137
10	Kepulauan Riau	310	13	17
11	DKI Jakarta	571	23	32
12	Jawa Barat	3,433	141	198
13	Jawa Tengah	4,637	190	280
14	DI Yogyakarta	677	28	41
15	Jawa Timur	4,607	189	289
16	Banten	935	38	52
17	Bali	507	21	32
18	Nusa Tenggara Barat	445	18	29
19	Nusa Tenggara Timur	6,203	254	416
20	Kalimantan Barat	3,421	140	188
21	Kalimantan Tengah	4,911	201	270
22	Kalimantan Selatan	2,158	88	116
23	Kalimantan Timur	3,660	150	194
24	Kalimantan Utara	933	38	52
25	Sulawesi Utara	263	11	16
26	Sulawesi Tengah	1,026	42	60
27	Sulawesi Selatan	1,033	42	62
28	Sulawesi Tenggara	1,781	73	105
29	Gorontalo	150	6	9
30	Sulawesi Barat	315	13	19
31	Maluku	1,544	63	90
32	Maluku Utara	295	12	17
33	Papua Barat	1,642	67	91
34	Papua	7,897	324	427
	Total	**82,847**	**3,397**	**4,705**

Note: The provinces are arranged based on official numbering by the Ministry of Home Affairs (MoHA, 2017) (see Appendix A for more details).

3.2 Overall assessment

As presented in Table 4, the analysis finds that Indonesia's nationwide technical potential for solar PV capacity reach an upper limit of 19,835 GWp (19.8 TWp), with generation potential of 26,971 TWh/year, and taking up 24.4% (484,455 km^2) of Indonesia's total land mass for the most optimistic scenario (Scenario 1). Even in the more conservative estimates (Scenario 2, 3, and 4), Indonesia's PV technical potentials are found to range between 3.3 to 7.7 TWp, with generation potential of 4,700 to 10,500 TWh/year, taking up 4.34% to 9.85% of Indonesia's total land mass of 1.9 million km^2.

In comparison with the current national estimates, the results in this assessment are 16 to 95 times higher than MEMR's official technical potential estimate, that is 207 GWp. There is limited, publicly available information on the basis of that estimation. National Energy Council's Indonesia Energy Outlook 2017 listed Indonesia's solar theoretical and technical potential by converting land area with solar potential (in kWh/m^2/day) and assuming 15% module efficiency to that resource potential; resulting in approximately 3,700 GW of theoretical solar potential and 559 GW of technical potential, although this estimate appears to be revised to 207 GW in 2017, as listed in RUEN.

It should be noted, however, that technical potential only represents the upper-boundary estimate of development potential, not the actual potential that might actually be deployed (see Section 1.2 for more details). Given a more restrictive land cover/use constraints and policy and regulatory limits, the potential estimate (so-called economic or market potential) might be lower. It is also worth mentioning that real life limitations such as land acquisition, which might be difficult in reality, were not included in the assessment. Nevertheless, this estimate can provide better (geospatial) information regarding policymaking or power system planning related to solar power development in the country.

3.3 Technical potential on each island/archipelago

Generally speaking, the magnitude of the technical potential for capacity (and generation) is proportional to the corresponding suitable area. That is not to say that islands or provinces with larger administrative areas will have higher potential, as some might be excluded due to having large forest areas, for instance. That said, in most of the scenarios, Kalimantan (Borneo), Sumatra, and Papua islands are in the top three for the largest technical potential for solar PV given its large land mass.

When looking at province-level, Kalimantan Barat (West Kalimantan) (2.2 TWp), Kalimantan Timur (East Kalimantan) (1.6 TWp), and Kalimantan Tengah (Central Kalimantan) (1.4 TWp), respectively, are the top three provinces with the largest suitable areas, potential capacity, and potential generation (for Scenario 1). The order changed slightly when agricultural lands and plantation forest are taken from the Scenario 1 (Scenario 2), making East Kalimantan (1,1 TWp) in the first place replacing West Kalimantan (0.99 TWp), which is now in second place, and followed with Central Kalimantan (0.6 TWp) in the third place. Other provinces like Riau, North Sumatera (Sumatera Utara), South Sumatera (Sumatera Selatan), Papua (province), East Java (Jawa Timur), and Central Java (Jawa Tengah) are also amongst the largest potential for solar PV generation.

4 Discussion

This section further discusses how the nationwide technical potential presented in this work could support future energy planning for Indonesia, especially as the government has numerously stated its intent to focus on solar PV for its grand energy strategy, targeting 17.6 GW of solar installed capacity by 2035, where 76% (13.5 GW) is projected to come from utility-scale solar PV (IESR, 2021). Moreover, the geospatial assessment identified in this work could act as input to achieve solar energy target in the RUEN, that is 6.5 GW of solar installed capacity by 2025. While RUEN's target is currently under review by the National Energy Council (*Dewan Energi Nasional*, DEN), as the macroeconomic assumptions are no longer relevant with actual status (Setiawan, 2021), there is wide support to maintain renewable energy targets and even higher. Indonesian policymakers can also use the findings in this report to support rapid solar power development in the energy policy making and power system planning by PLN as stipulated in *Rencana Umum Penyediaan Tenaga Listrik* (RUPTL).

4.3 Current national electricity demand

Like most countries, Indonesia is facing an economic downturn and reduced energy demand due to the COVID-19 pandemic. Latest update on the upcoming RUPTL (2021–2030) suggests that the government plans to cut 15.5 GW, mainly fossil-fueled power plants, out of the originally planned 56.4 GW power capacity from the previous RUPTLN (2019–2028) (Umah, 2021a). In the upcoming RUPTL (2021–2030), PLN plans to add 3.7 GW of combined "various renewables" that is solar PV, wind power, and waste-to-energy plants, although the specific ratio for solar PV is still unclear (Umah, 2021b). However, it is clear from the previous RUPTL (2019–2028) that solar PV has not been a priority in the power system planning. In the previous RUPTL (2019–2018), solar PV only accounts for 1.6% (908 MW) out of the total 56.4 GW of planned power capacity addition. This number is very small compared to the potential that is presented in this work. Given the current power system adjustment due to COVID-19 pandemic, the government, particularly MEMR and PLN, could use the opportunity to re-plan the priorities used in the upcoming RUPTL to achieve 23% renewable energy targets by 2025.

4.3.1 Case study in Bali

Electricity in Bali is supplied from a total of 1,042 MW inland power generation—which includes a total of 408 MW fossil fuel power plants, diesel–gas power plants (208 MW), and a coal-fired power plant (420 MW)—and through a 150 kV submarine cable transmission to Java's system (400 MW) (PLN, 2019). According to data from PLN Bali (2020), Bali's latest power system peak demand is at 980 MW (as of January 2020).

Figure 12. Bali's power system. Adapted from PLN's 2019 RUPTL

Heavily concentrated on tourism activities, electricity in Bali is primarily consumed by residential (40%) and business (50%) consumer groups (PLN, 2019). Bali's electricity demand is expected to grow at an annual average of 6.5% between 2019–2028, according to PLN's 2019 RUPTL. While electricity demand is impacted heavily due to COVID-19, PLN originally plans to add 100 MW of utility-scale solar by 2025, of which 50 MW (Bali 2 x 25 MW ground-mounted solar projects) are already won and are currently waiting for a power purchase agreement (PPA) signing (IESR, 2019b, 2021).

While the current target for solar PV is relatively small given Bali's potential, Bali's future electricity demand can be met using more solar power in the mix, as the technical potential suggests (see Appendix C). IESR analysis finds that Bali has a total of 26.4 GWp of solar PV technical potential (Scenario 2), with generation potential of 40.5 TWh/year across the nine regencies (see Table C-1 in Appendix C). Furthermore, to complement solar's intermittency, Bali also shows an enormous potential for pumped hydroelectric energy storage (PHES), capable of storing 559.9 GWh of electricity for all cost classes) (see Appendix D for more details). With both solar PV and PHES potential, Bali can strive for a 100% renewable energy system in the near future. The more ambitious use of solar energy will also be inline with the Bali Governor Regulation No. 45/2019 on Bali Clean Energy. Additionally, the gubernatorial regulation also stipulates commercial, industrial, social, and residential buildings with floor space higher than 500 m2 to install rooftop solar of at least 20% of its installed power capacity—of which PLN Bali noted that there is as much as 237 MWp of potential—or 20% of available roof space (PLN Bali, 2020).

4.3.2 Case study in Sumba Island

Sumba is located in East Nusa Tenggara (Nusa Tenggara Timur) province. Being an isolated island, Sumba's power system is dominated by diesel generators (9 units totaling 11 MW) and several renewables-based power generation such as micro hydro (4 units totaling 3 MW) and a solar power plant (1 MW) according to latest RUPTL (PLN, 2019)

Figure 13. Sumba Island's power system map. Adapted from PLN's 2019 RUPTL

Electricity demand (as shown by the sales realization) in East Nusa Tenggara (specific data on Sumba is unavailable) is primarily dominated by the residential segment (60%), then followed by business customer group (24%), public (11%)—which includes public hospitals and schools—and industrial users (4%) in 2018, according to PLN's RUPTL 2019–2028. According to PLN's RUPTL, It has shown an estimated average electricity demand growth of 7% between 2015–2018 and is projected to grow at 8.8% over the next ten year (2019–2028).

Specific to Sumba's system, in the 2019's RUPTL, PLN indicates their plan to add a total of 16 MW of biomass power plants, a total of 20 MW gas engine power plants, a total of 8.6 MW of micro hydro power plants, and 3.8 MW of solar/wind power plant over the next ten years. More recently, however, the government has occasionally stated their interest in developing large-scale solar farms in Sumba, often dubbed as "Sumba solar barn initiative" (*Sumba Lumbung Surya*), with a 2 GW target out of the 13.5 GW large-scale solar target by 2035 (IESR, 2021; PJCI, 2020). The Governor of East Nusa Tenggara has also shown support for this initiative noting that the island will be a center for solar PV development with up to 20 GW of potential (Bere, 2020; Lewokeda, 2020). The initiative is expected to deliver electricity not only across East Nusa Tenggara, but also to Bali, Java and other load centers using high voltage direct current (HVDC) transmission systems, according to the energy ministry (EBTKE, 2020). While there are no specific details regarding this initiative yet, the findings of this assessment support the idea, as Sumba is shown to have a total of 133 GWp of solar PV technical potential (for Scenario 2) with generation potential of 216 TWh/year (see Appendix E for more details). The potential (capacity) is highest in the East Sumba (Sumba Timur) regency (60%), followed by Central Sumba (Sumba Tengah) (21%) and Southwest Sumba (Sumba Barat Daya) (10%). West Sumba (Sumba Barat) fills the last place at only 7% out of the 133 GWp (see Table E-1).

5 Conclusion and Recommendations

5.1 Conclusion

A geospatial assessment of Indonesia's nationwide solar PV technical potential has been conducted using publicly sourced national and international data. The analysis finds that Indonesia's solar PV technical potential capacity ranges between 3,396 GWp up to 19,835 GWp (depending on land-use exclusions scenarios). In terms of generation potential, Indonesia can achieve 4,705 – 26,791 TWh/year, by taking up 4.34% to 24.43% of the total land mass (depending on the scenario). The results also show that Indonesia's utility-scale solar PV potential is well above (16 to 95 times larger) the current national official estimate, that is 207 GW. The findings presented in this work could be used to support solar power development in the country, while at the same time, meet future electricity demand and achieve renewable energy targets.

Table 9. Summary of Indonesia's solar PV technical potential assessment

Scenarios	Suitable area (km²) *(% of Indonesia's total land mass)*	Solar PV Technical Potential	
		Capacity (GWp)	Generation (TWh/year)
Scenario 1 (S1): Base exclusions (protected areas, forested areas, water bodies, wetland areas, airports and seaports) + slope exclusion (>10°)	484,455 *(24.43%)*	19,835	26,972
Scenario 2 (S2): S1 + agricultural lands (both pure and shrub-mixed) and plantation forest areas exclusions	187,806 *(9.85%)*	7,700	10,508
Scenario 3 (S3): S2 + transmigration and settlements areas exclusions	153,915 *(8.07%)*	6,310	8,541
Scenario 4 (S4): S2 + dry shrub exclusion	82,847 *(4.34%)*	3,397	4,705

Notes: Scenario 1 includes dry shrub, savanna, bare land, mining, transmigration, settlements, plantation forests, pure dry and mixed agricultural lands; Scenario 2 excludes plantation forests, pure dry and mixed agricultural lands from Scenario 1; Scenario 3 excludes transmigration and settlements from Scenario 2; and Scenario 4 excludes dry shrub from Scenario 2;

5.2 Recommendations

To follow up this assessment, it is recommended that:

1. The government updates the nation-wide solar technical potential figure, as to reflect more detailed potential for solar energy development in Indonesia. Current assessment shows Indonesia's solar potential is higher than current official estimate and it has the potential to supply Indonesia's future energy demand.
2. Identification of prospective locations at provincial levels is performed together with the provincial government and respective PLN's regional offices. Case studies such as for Bali and Sumba could be entry points to a more detailed planning. Assessment should include current and projection of electricity supply and demand in the area, grid study, financing needs, as well as related policies and incentives.
3. Further technical assessments can be conducted, particularly to zoom in specific locations at cities/regencies level and even smaller, not only for utility/large-scale solar, but also for floating solar and rooftop solar.

6 References

ADB. (2018a). Environmental and Social Impact Assessment Report (ESIA) – Likupang 21 MWp Solar Project. Asian Development Bank (ADB). https://www.adb.org/projects/documents/ino-51209-002-eia-0

ADB. (2018b). Environmental and Social Impact Assessment Report (ESIA) – Lombok 3 x 7 MWp Solar Projects. Asian Development Bank (ADB). https://www.adb.org/projects/documents/ino-51209-002-eia

Bere, S. M. (2020). Gubernur NTT Jadikan Sumba sebagai Pusat Listrik Tenaga Surya untuk Indonesia Halaman all—Kompas.com. https://regional.kompas.com/read/2020/10/06/09334651/gubernur-ntt-jadikan-sumba-sebagai-pusat-listrik-tenaga-surya-untuk?page=all

BSN. (2010). SNI 7645:2010—Land cover classification. Indonesia's National Standardisation Agency (BSN). https://www.big.go.id/assets/download/sni/SNI/15.%20SNI%207645-2010%20Klasifikasi%20penutup%20lahan.pdf

EBTKE. (2020). Pemerintah Dorong Inisiatif Lumbung Energi Surya di Sumba. https://ebtke.esdm.go.id/post/2020/12/18/2739/pemerintah.dorong.inisiatif.lumbung.energi.surya.di.sumba

Global Forest Watch. (2020). Land Cover Indonesia. https://data.globalforestwatch.org/datasets/b1126d52d6c5416496339aeb250d9b39

IESR. (2019a). Residential Rooftop Solar Potential: Technical and Market Potential in 34 Provinces in Indonesia. Institute for Essential Services Reform (IESR). https://iesr.or.id/en/pustaka/residential-rooftop-solar-potential-in-34-provinces-in-indonesia

IESR. (2019b). Indonesia Clean Energy Outlook: Tracking Progress and Review of Clean Energy Development in Indonesia.

IESR. (2020). National Energy General Plan (RUEN): Existing Plan, Current Policies Implication, and Energy Transition Scenario. Institute for Essential Services Reform (IESR). https://iesr.or.id/en/pustaka/ruen-existing-plan-current-policies-and-energy-transition-scenario

IESR. (2021). Indonesia Energy Transition Outlook 2021: Tracking Progress of Energy Transition in Indonesia. Institute for Essential Services Reform. https://iesr.or.id/en/pustaka/indonesia-energy-transition-outlook-ieto-2021

Lewokeda, A. (2020). Pulau Sumba direkomendasikan untuk bangun PLTS 20.000 MW. Antara News NTT. https://kupang.antaranews.com/berita/38270/pulau-sumba-direkomendasikan-untuk-bangun-plts-20000-mw

MEMR. (2016). Indonesia's Solar Energy Potential Map. Ministry of Energy and Mineral Resources (MEMR).

MoEF. (n.d.). Peta penutupan lahan Indonesia. Retrieved March 16, 2021, from http://webgis.menlhk.go.id:8080/pl/pl.htm

MoHA. (2017). Home Affairs Minister Regulation (MoHA) No. 137 of 2016 regarding Code and Government Administrative Area Data. https://www.kemendagri.go.id/files/2019-05/Kode&Data%20Wilayah/Permendagri%20137-2017.pdf

NREL. (2012). U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy12osti/51946.pdf

NREL. (2013). Land-Use Requirements for Solar Power Plants in the United States. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy13osti/56290.pdf

NREL. (2016). Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results. National Renewable Energy Laboratory (NREL). https://www.nrel.gov/docs/fy15osti/64503.pdf

PJCI. (2020, December 17). Energy Talk Series 6: Lumbung Energi Surya Di Sumba Untuk Indonesia. https://www.youtube.com/watch?v=SAneXyVTxdU&ab_channel=Id_smartgrid

PLN. (2019). PLN's Electricity Supply Business Plan 2019–2028.

PLN Bali. (2020). PLN Bali's presentation on Bali's power system.

Setiawan, V. N. (2021, January 27). Jurus Baru DEN untuk Kejar Target Bauran Energi. https://katadata.co.id/sortatobing/ekonomi-hijau/60113a1b31a29/jurus-baru-den-untuk-kejar-target-bauran-energi

Umah, A. (2021a). Konsumsi Listrik Melandai, Pembangkit Baru Diciutkan 15,5 GW. News. https://www.cnbcindonesia.com/news/20210113181356-4-215722/konsumsi-listrik-melandai-pembangkit-baru-diciutkan-155-gw

Umah, A. (2021b). Pembangkit Listrik Tambah 40,9 GW Hingga 2030, Ini Rinciannya. News. https://www.cnbcindonesia.com/news/20210312132641-4-229680/pembangkit-listrik-tambah-409-gw-hingga-2030-ini-rinciannya

UNEP-WCMC & IUCN. (2016). Protected Planet Report 2016. UNEP World Conservation Monitoring Centre (UNEP-WCMC) and International Union for Conservation of Nature (IUCN). https://wdpa.s3.amazonaws.com/Protected_Planet_Reports/2445%20Global%20Protected%20Planet%202016_WEB.pdf

USAID & NREL. (2017). Renewable Energy Zone (REZ) Transmission Planning Process: A Guidebook For Practitioners. National Renewable Energy Laboratory (NREL).

Appendix A - Land cover classification in Indonesia

Land cover data used in this work is sourced from 2017's Ministry of Environment and Forestry (MoEF) data (1:250,000 scale), which are available online at: http://geoportal.menlhk.go.id/arcgis/rest/services/KLHK_EN (Metadata, if link is broken)

The MoEF classifies Indonesia's national land cover into 23 classes (including cloud/no data) with 7 forest classes and 15 non-forest classes (16, if including cloud/no data). This classification standardization is based on the needs and interest of MoEF, and is based on the national standard SNI 7645-2010 (MoEF, n.d.). Table A-1 presents the classification made by the MoEF.

Table A-1. Land cover classification by MoEF

No.	Land cover class (Indonesian)	Land cover class (English)	Category[4]	Notes
1	Hutan lahan kering primer	Primary dryland forest	Primary forest	X
2	Hutan lahan kering sekunder	Secondary dryland forest	Secondary forest	X
3	Hutan rawa primer	Primary swamp forest	Primary forest	X
4	Hutan rawa sekunder	Secondary swamp forest	Secondary forest	X
5	Hutan mangrove primer	Primary mangrove forest	Primary forest	X
6	Hutan mangrove sekunder	Secondary mangrove forest	Secondary forest	X
7	Hutan tanaman	Plantation forest (man-made)	Plantation forest	✓
8	Belukar	Dry shrub	Grassland	✓
9	Belukar rawa	Swamp shrub	Wetland	X
10	Sabana/padang rumput	Savannah	Grassland	✓
11	Pertanian lahan kering	Pure dry agricultural land	Cropland	✓
12	Pertanian lahan kering campur	Shrub-mixed dry agricultural land	Cropland	✓
13	Perkebunan	Estate crops (plantation)	Cropland	X
14	Sawah	Paddy field	Cropland	X
15	Transmigrasi	Transmigration	Settlements	✓
16	Tambak	Fish pond (aquaculture)	Other land	X
17	Tanah terbuka	Bare land	Other land	✓
18	Pertambangan	Mining	Other land	✓
19	Pemukiman	Settlements	Settlements	✓
20	Bandara/pelabuhan	Airport/harbour	Other land	X
21	Badan air	Open water	Bodies of water	X
22	Rawa	Open swamp	Wetland	X
23	Awan (no data)	Clouds (no data)	No data	X

Note: X indicates that the land cover class is excluded for technical potential assessment due to several different reasons explained in Section 2.2. General exclusions include forest areas, wetland, bodies of water, several cropland areas, and seaport/airport. On the other hand, ✓ indicates that the land cover type is assumed to be suitable for solar PV development (as summarized in Table 1) and further made into four different scenarios (as summarized in Table 3).

[4]Further categorization by the World Resources Institute (Global Forest Watch, 2020)

Appendix B - Indonesia's provincial administrative boundaries map

Figure B-1. Map of Indonesia's provincial administrative boundaries

Appendix C - Bali's solar PV technical potential (Scenario 2)

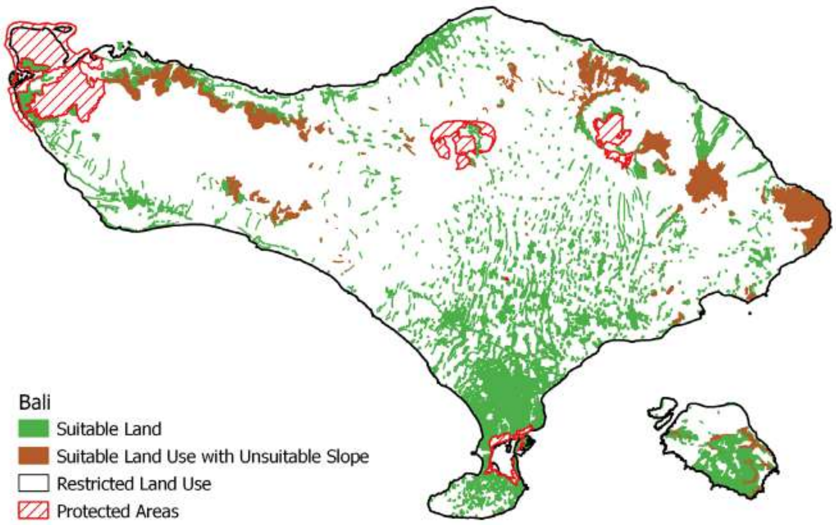

Figure C-1. Suitable area map for solar PV installation in Bali (Scenario 2)

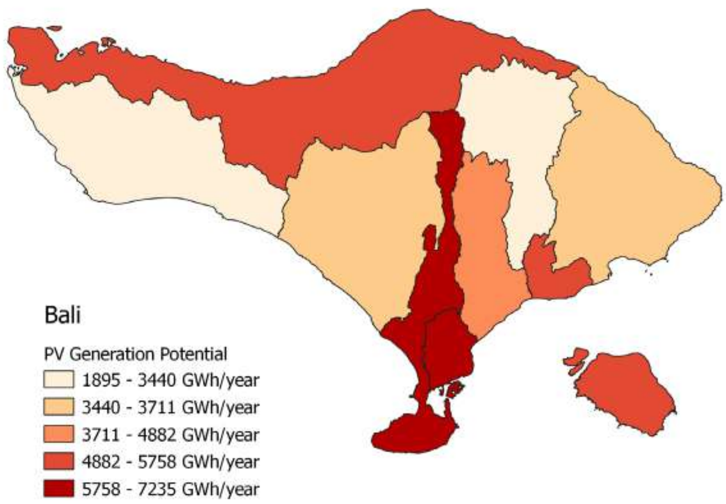

Figure C-2. Solar PV technical generation potential map in Bali (Scenario 2)

Table C-1 Summary of solar PV technical potential in Bali (Scenario 2)

Regency/city	Suitable Land (km^2)	Potential Capacity (GWp)	Potential Generation (GWh/year)
Badung	111.88	4.59	7,234.73
Bangli	33.03	1.35	1,894.88
Buleleng	86.53	3.55	5,418.47
Gianyar	70.15	2.88	4,361.63
Jembrana	53.21	2.18	3,295.04
Karangasem	56.96	2.34	3,536.67
Klungkung	78.05	3.20	5,012.64
Kota Denpasar	94.13	3.86	6,266.45
Tabanan	59.91	2.46	3,548.97
Total	**643.85**	**26.40**	**40,569.47**

Appendix D - Bali's pumped hydroelectric energy storage potential

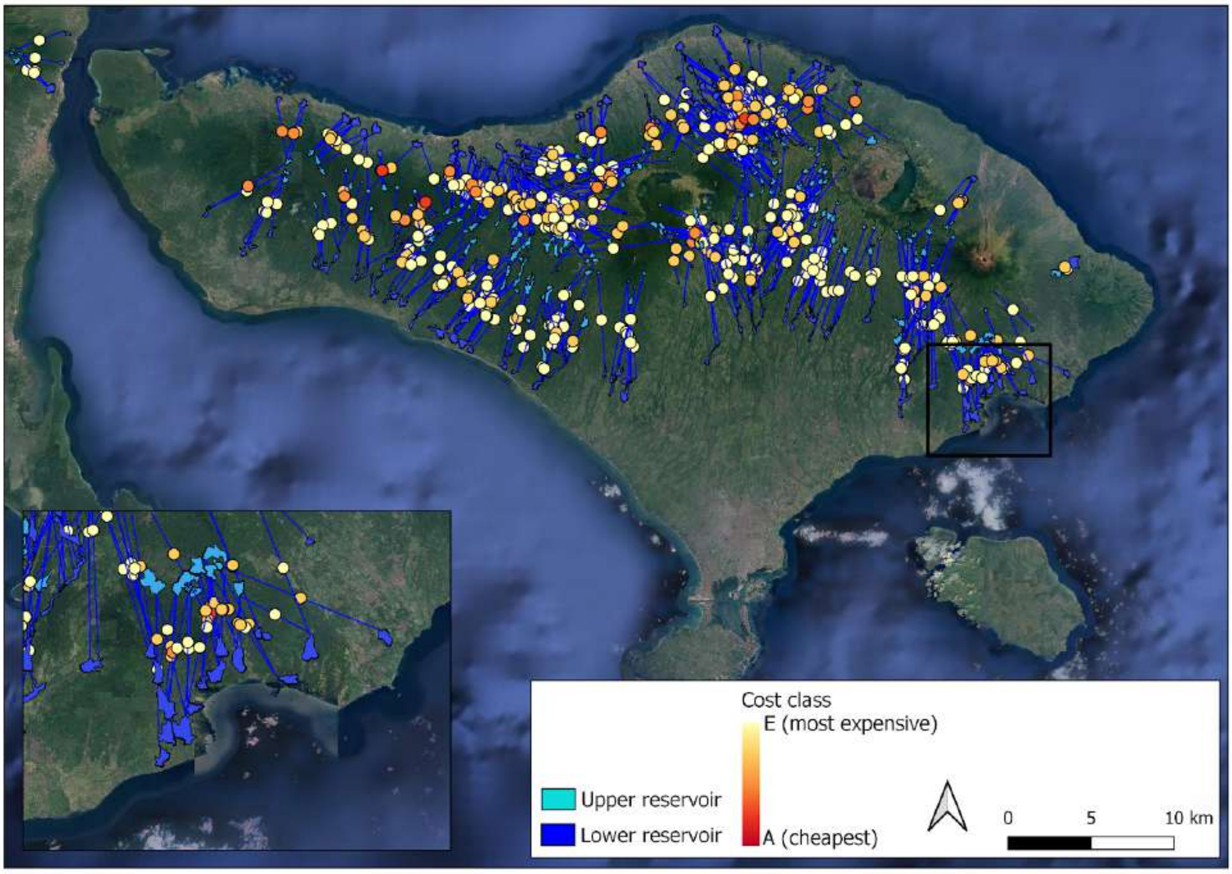

Figure D-1 Pumped hydroelectric energy storage (PHES) potential in Bali

Table D-1 Summary of pumped hydroelectric energy storage (PHES) potential in Bali

Cost_class	Total number of PHES	Energy (GWh)	Storage time (h)	Total energy (GWh)
A	0	2	6	0.0
	0	5	6	0.0
	1	5	18	0.3
	0	15	6	0.0
B	0	2	6	0.0
	1	5	6	0.8
	3	5	18	0.8
	4	15	6	10.0
C	10	2	6	3.3
	31	5	6	25.8
	29	5	18	8.1
	21	15	6	52.5
D	54	2	6	18.0
	51	5	6	42.5
	65	5	18	18.1
	50	15	6	125.0
E	74	2	6	24.7
	73	5	6	60.8
	78	5	18	21.7
	59	15	6	147.5
Total energy from all cost-classes and storage (GWh)				**559.9**

Notes:
- The calculated PHES potential is technical potential
- Conservation areas have been excluded from the calculation of potential PHES, but areas prone to disasters have not

Appendix E - Sumba's solar PV technical potential (Scenario 2)

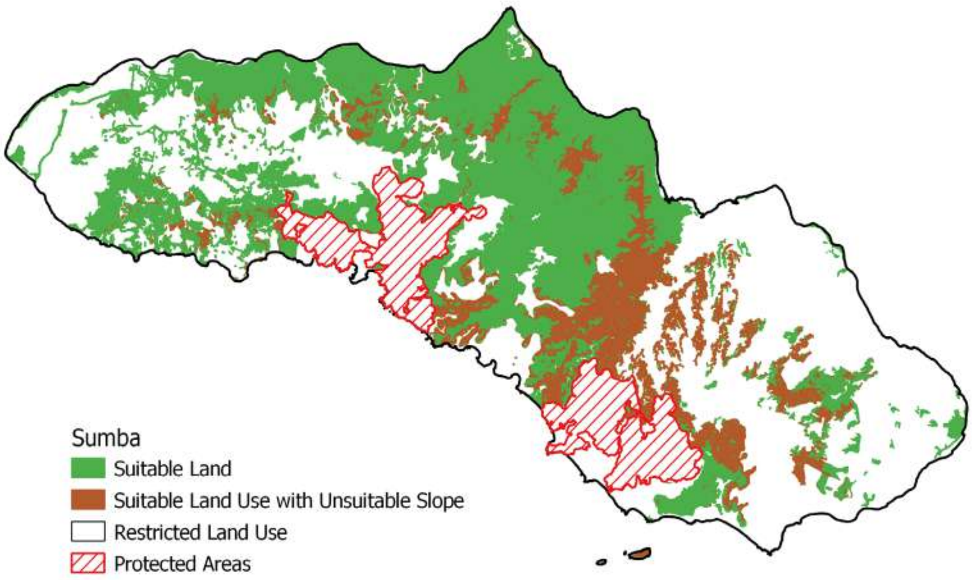

Figure E-1. Suitable area map for solar PV installation in Sumba Island (Scenario 2)

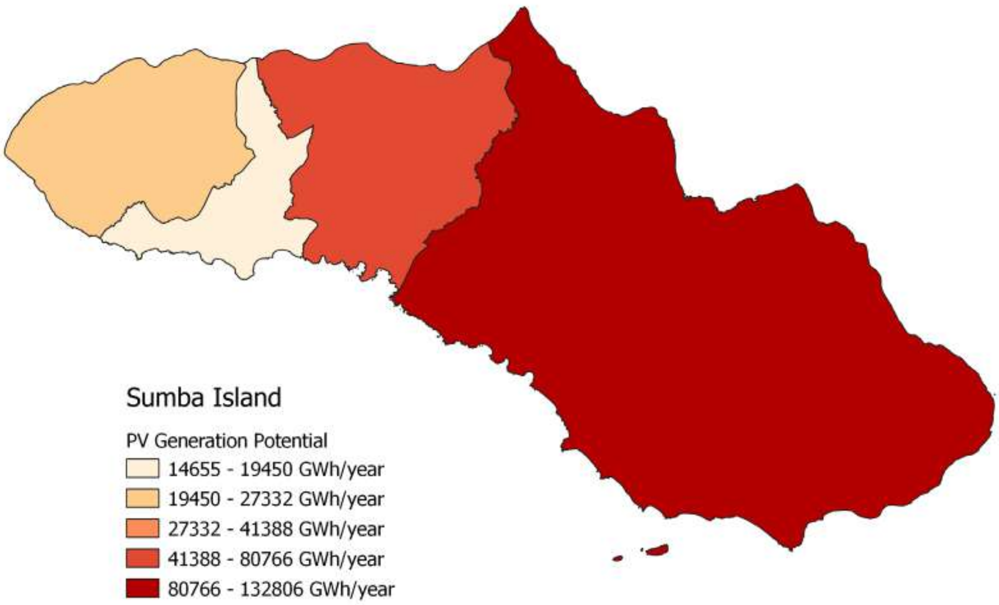

Figure E-2. Solar PV technical generation potential map in Sumba Island (Scenario 2)

Table E-1 Summary of solar PV technical potential in Sumba Island (Scenario 2)

Regency	Suitable Land (km²)	Potential Capacity (GWp)	Potential Generation (GWh/year)
Sumba Barat	227.90	9.34	14,655.32
Sumba Barat Daya	356.25	14.61	22,646.70
Sumba Tengah	686.77	28.16	46,073.12
Sumba Timur	1,973.82	80.93	132,805.65
Total	**3,244.75**	**133.03**	**216,180.79**

IESR
Institute for Essential Services Reform

Jalan Tebet Barat Dalam VIII No. 20
Jakarta Selatan 12810 | Indonesia
T: +62 21 2232 3069
F: +62 21 8317 073
iesr.id iesr
www.iesr.or.id