Revisiting Renewable Energy Map in Indonesia: Seasonal Hydro and Solar Energy Potential for Rural Off-Grid Electrification (Provincial Level)

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Abstract. Regarding the acceleration of renewable energy diffusion in Indonesia as well as achieving the national energy mix target, renewable energy map is essential to provide useful information to build renewable energy system. This work aims at updating the renewable energy potential map, *i.e.* hydro and solar energy potential, with a revised model based on the global climate data. The renewable energy map is intended to assist the design off-grid system by hydropower plant or photovoltaic system, particularly for rural electrification. Specifically, the hydro energy map enables the stakeholders to determine the suitable on-site hydro energy technology (from pico-hydro, micro-hydro, mini-hydro to large hydropower plant). Meanwhile, the solar energy map depicts not only seasonal solar energy potential but also estimated energy output from photovoltaic system.

Key words: Hydro energy, solar energy, off-grid, rural electrification.

1 Introduction

Renewable energy is becoming a global issue as the crisis of fossil energy emerged nowadays. Indonesia as a part of the international community shares the concern on the environment and development issues [1–3]. Indonesia is a country with vast natural resources and significant reserves in oil, gas and coal. It is also abundant in reserves of renewable energy sources. There is also an enormous potential to develop and use clean energy sources such as hydropower (75 000 MW), geothermal (29 164 MW), biomass (49 810 MW), ocean (46 GW), solar (4.80 kW h m^{-2} d^{-1}), and wind energy (3 m s^{-1} to 6 m s^{-1}) [1–5].

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Despite these facts, Indonesia is currently facing an energy crisis. The average rate of energy consumption is approximately 7 % in the last decade, while the rate of energy supply is limited. Indonesia is heavily dependent on fossil fuel, particularly on oil. Oil dominates of 50 % of the primary energy mix, followed by coal at 32 %, gas at 19 %, geothermal at 1.3 %, hydro at 2.9 % and the rest is supplied by other renewable energy resources [2, 3]. Moreover, the high growth of fossil energy consumption will lead to environmental problems, particularly in high CO_2 emissions that cause global warming.

Recently, the government of Indonesia committed to reducing greenhouse gasses (GHG) emissions up to 29 % in 2030 through domestic efforts and 41 % with international assistance [1, 2, 6]. Clean energy utilization, termed as renewable energy utilization and energy efficiency according to Presidential Regulation No. 4 and No. 5 year 2010 [1–4] is one of the priority activities in reducing GHG emission in the energy sector: National energy policy involves energy conservation and energy diversification to increase the share of new and renewable energy use in the national primary energy mix. Furthermore, energy mix target focuses to establish 17 % new and renewable energy in energy mix (with an assumption of energy elasticity less than one in 2025 to optimize new renewable energy sources) [2, 3]. To date, the total installed capacity of national electricity is 30 941 MW, with 83 % electricity supplied by the national electricity company (PT. PLN), and the rest by the independent power producers (IPP) at 14 % and private power utility at 3 % [1]. Also, it is estimated that around 93% of Indonesia's inhabitants have access to electricity.

Despite the fact of high electrification ratio achieved in 2017, several areas, *i.e.* coastal and rural area, are facing electricity crisis with electricity demand higher than the supply or no electricity supply into these areas [6]. Since rural areas often face difficulties to get access to national electricity grid due to economic and geographical barriers, utilization of renewable energy resources is likely the only option for generating electricity [6, 7]. Moreover, in order for national energy mix target to achieve acceleration of renewable energy utilization whose technologies are technically and economically proven should be prioritized [6–9]. However, it is known that the renewable energy potential is site-specific and intermittent and hence, temporal (or seasonal) and spatial data of renewable energy potential is required to map the feasible energy generation and the selection of renewable energy technology at different sites. Herein the revised maps of renewable energy potentials, particularly hydro and solar energy, based on the global climate data to support the stakeholders of renewable energy development in Indonesia are presented.

2 Method

2.1 Geographical and climatological data

Data used for this study originated from secondary sources. Climate was represented by precipitation, air temperature, and sunshine duration. Climate data has been obtained from University of East Anglia Climate Research Unit (CRU) (CRU Climatology version 2.0—CRU CL 2.0) [10]. These data provide the mean monthly precipitation, air temperature, and sunshine duration at a (10 × 10) min spatial resolution. The precipitation and air temperature were used for hydrological simulation and later to estimate the hydropower, whilst the sunshine duration was used to estimate the solar power.

Land cover was collected from The Global Land Cover by National Mapping Organizations (GLCNMO) developed by Geospatial Information Authority of Japan (GSI) and Chiba University, Japan. The data were prepared by using MODIS data in a grid of 500 m [11]. The heterogeneous land cover was converted into crop factor which was later used to calculate soil water holding capacity and potential evapotranspiration for hydrological modelling simulation.

The digital elevation model (DEM) was used 30 m—Shuttle Radar Topography Mission (SRTM). The DEM was used to generate slope, river network model, and the natural falling head. For hydrological modelling, DEM should be pre-processed. As the presence of sinks (a pixel value lower than the surroundings) and peaks (a pixel where no adjacent pixels are higher) in DEM might result in an erroneous river flow direction raster, they were filled to ensure proper delineation of river basins and river networks. This step removed small imperfections in the data. After DEM corrected from sinks and peaks, the next step is deriving flow direction. The method of deriving flow direction from a DEM is based on literature [12]. Flow direction was determined by the direction of steepest slope from each cell. Flow direction determined the direction in which water would flow out of the pixel. The accumulated flow was based on the number of pixels that flowing into each pixel. Output pixels with a high flow accumulation were areas of concentrated flow and were used to identify the river network model. In summary, the schematic representation of geographical and climatological data collection and processing is depicted in Figure 1.

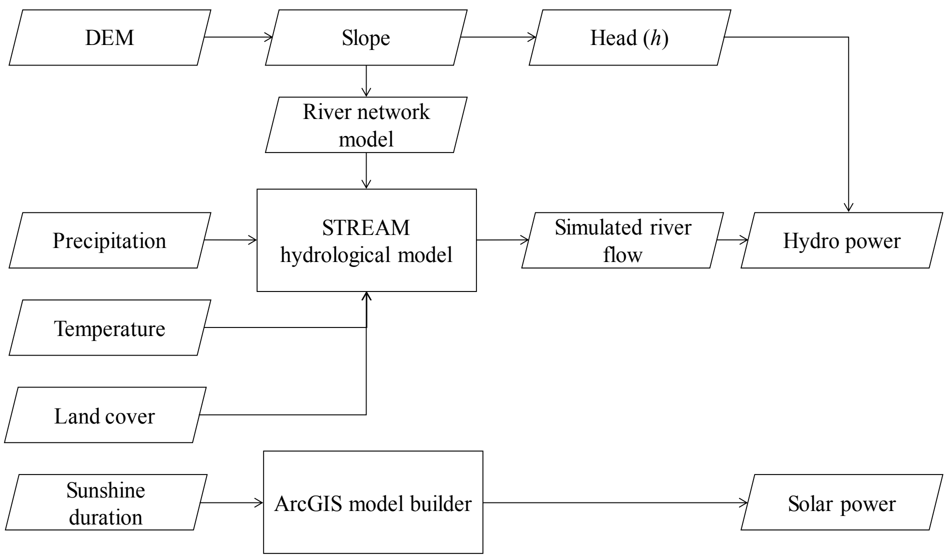


Fig. 1. Flow diagram of global climate data collection and processing for hydro and solar energy estimation.

2.2 Estimation of hydro energy output

Hydro power is classified by the net power output from the system. Typically, hydropower can be classified into picohydro, microhydro, minihydro, small, medium and large hydropower. In order to assess the net power output of the employment hydro energy potential was calculated using the following formula:

$$E_{hydro} = \eta_G \times \eta_T \times \rho \times \dot{\forall} \times g \times h \quad (1)$$

Where η_G is the efficiency of generator, η_T is the efficiency of hydro-turbine, ρ is the density of water (kg m^{-3}), $\dot{\forall}$ is the volumetric flow rate (m^3 s^{-1}), g is the gravitational acceleration (9.8 m s^{-2}), and h is the falling height, head (m). It should be noted that the hydro energy potential estimation in this study doesn't consider the energy sources from hydro kinetic energy. The η_G spans from 0.85 to 0.93, while the η_T spans from 0.75 to 0.95 depending on the type of the turbine used in the system.

The $\dot{\forall}$ was assumed as river discharge flow in drainage network. $\dot{\forall}$ was simulated based on hydrological modelling. STREAM hydrological model is used. STREAM [13] describes the hydrological cycle of a drainage basin as a series of storage compartments and flows. It applies Thornthwaite-Mather's water balance approach to calculate flow discharges along drainage networks derived from a DEM. The main inputs to the model are climate data (maps of precipitation and temperature), a DEM, land cover maps and water holding capacity maps. Potential and actual evapotranspiration are calculated in STREAM at the so-called soil compartment represented by a grid cell. Following this, storage of water in a grid cell is estimated according to the difference between evapotranspiration and precipitation. Finally, discharge per time step is calculated according to excess of water in each grid cell and baseflow from groundwater storage. Calibration of STREAM model has been successfully done and documented in literature [14, 15]. The *h* is estimated based on the different elevation between two pixels on digital elevation model. Firstly, the slope map is generated from the DEM, later the tangent of slope in degree is used to estimate the rise (different height) over the run (spatial resolution of the DEM).

2.3 Estimation of solar energy output

Estimation of solar energy is employed in ESRI ArcGIS version 10 model builder. This allows us for calculating solar power in spatial-temporal scale. The daily energy output (E_{PV}) of photovoltaic (PV) system in this study was revised. In general, the daily energy output from a PV array is calculated using peak hours formula as below:

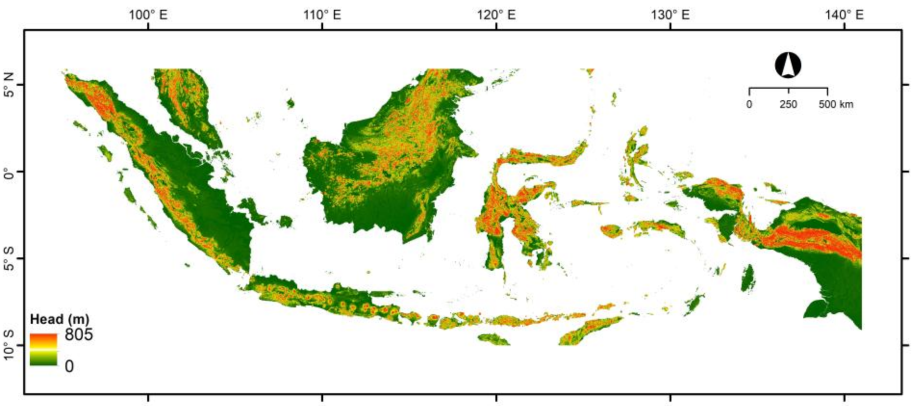
$$E_{PV} = \frac{P_{rated} \times S}{\Phi_{AM1.5G}} \tag{2}$$

Where P_{rated} is rated peak power of PV panel (Wp), S is insolation (kW h m^{-2} per day), and $\Phi_{AM1.5G}$ is radiative power flux at peak sun (W m^{-2}). This formulation means that a PV panel receives constant $S/\Phi_{AM1.5G}$ peak hours of sun per day (a square-wave function). However, this leads an overestimation of the energy output from PV array since power conversion efficiency of PV declines at lower irradiation. Therefore, the radiative power flux in this work was modelled as a Gaussian wave instead of a square wave.

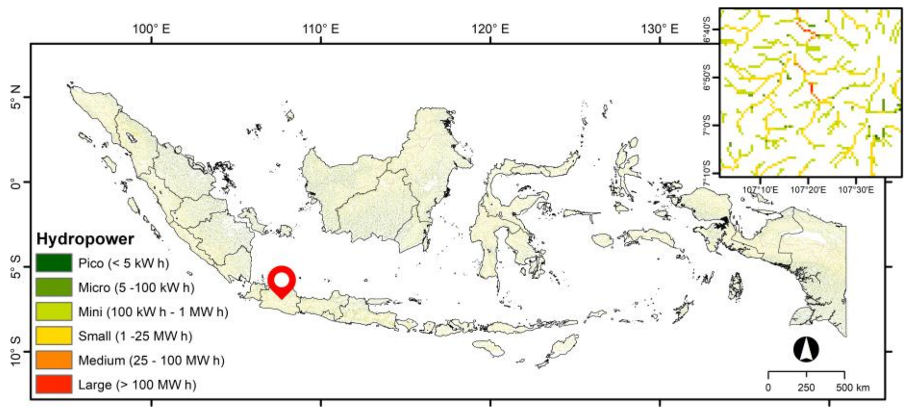
3 Results and discussion

As a tropical country, the seasonal variation in this work is discussed in the wet and the dry season which occurs approximately from October to March and from April to September, respectively. Therefore, the results of renewable energy potential map are simplified into two maps, *i.e.* the wet and the dry season.

The hydro energy potential is distributed in a manner as shown in Figure 2. It is again worth to note that hydro energy potential estimation neglects the kinetic energy potential by the water flow, instead it is determined from a classical approximation of potential energy due to the natural falling height *h*. Furthermore, the estimated hydro energy potential is used to classify the hydropower plant suitable at certain sites: picohydro (< 5 kW h), microhydro (5 kW h to 100 kW h), minihydro (100 kW h to 1MW h), small hydropower (1 MW h to 25 MW h), medium hydropower (25 MW h to 100 MW h) and large hydropower (>100 MW h) plant [16]. The topographical map of the falling head *h* based on the digital elevation data is depicted in Figure 2a and the hydro energy distribution maps are shown in Figure 2b and Figure 2c.



(a)



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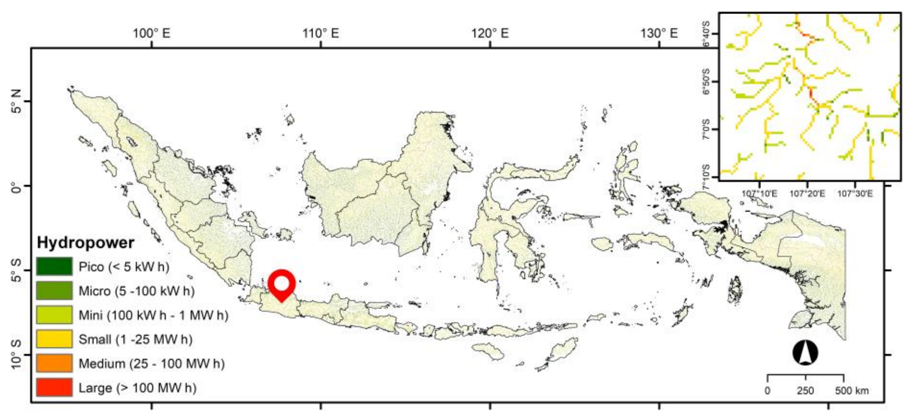
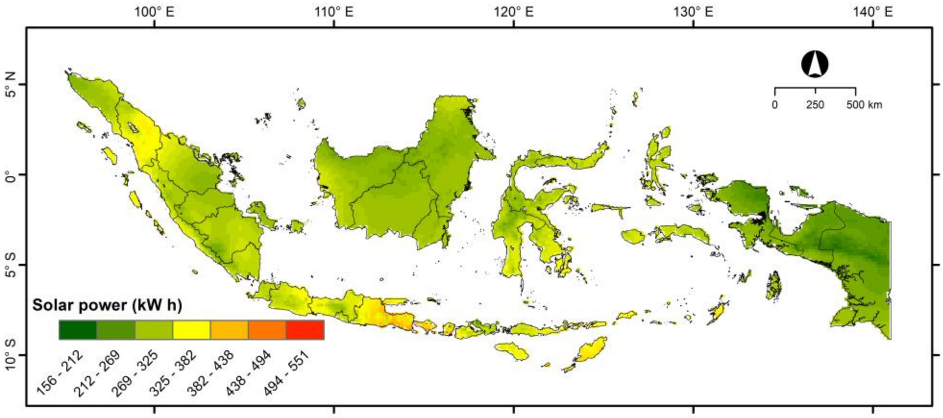


(c)

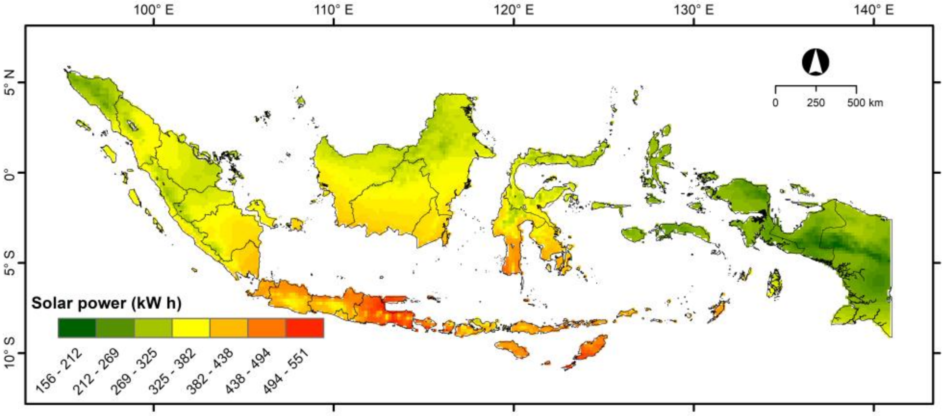
Fig. 2. (a) Head profile based on digital elevation data. Seasonal hydro energy potential during (b) wet and (c) dry season. Inset of figures depicts an enlarged map of hydropower distribution in west Java as indicated by location symbol (red) in the map.

As shown in the above maps, the hydro energy potential in Indonesia is dominated by the pico to minihydro power plant. A more clear view on how the hydro energy potential changes due to seasonal change in west Java is indicated in the inset of Figure 2b and Figure 2c. The estimated hydro energy potential in this study is verified by other reported works which shows the potential of developing micro and mini hydropower plant [17, 18]. For example, Anugrah et al. [19] evaluating the microhydro power plant in West Sumatera with a capacity of 30 kW to 40 kW in which their system can be improved to yield an annual hydropower spanning from 170 MW h to 275 MW h. Meanwhile, other study by Kumara et al. [20] reports that 43.2 kW h hydropower can be generated in Bali where the hydro energy potential is lower than that in West Sumatera.

Large hydropower plants are only identified in five big islands in Indonesia. The order of the most potential locations is the following: Kalimantan (eastern, middle, and western part), Papua (eastern and middle part), Sulawesi (southeast and middle part), Sumatera (northern and western part), Java (western and middle part). This finding is in good agreement with the study reported by Purwanto and co-workers [21]. The study has concluded that 60 % of total hydropower potentials are located in Kalimantan and Papua. The combination of the high river flows from the large watersheds, especially in the large island, and the variation of topographic slope generates abundant hydropower potential.



(a)



(b)

Fig. 3. Profile of estimated solar energy potential in Indonesia during (a) wet and (b) dry season.

The central attention is now turned to the distribution of solar energy potential in Indonesia. In general, solar energy potential in Indonesia is distinguished into two different areas: The Western part of Indonesia features with an average irradiation of (4.50 ± 0.45) kW h m^{-2} per day and the Eastern part of Indonesia is characterized by an average irradiation of (5.10 ± 0.45) kW h m^{-2} d^{-1} [8, 9]. In this work, the solar irradiation is spatially-varying from (1.3 to 3.6) kW h m^{-2} per day (data not shown) and slightly lower than that reported by Rumbayan et al. [22] and Veldhuis and Reinders [23]. The monthly solar irradiation also does not vary significantly within the same season and fluctuates in a moderate extent thought the year.

Figure 3 presents the profile of solar energy available in terms of practical solar energy potential: The solar irradiation potential is already converted into solar energy potential generated in full PV-battery system occupying 350 Wp PV module in 100 m^2 area (DC/AC inverter's efficiency is set to 0.85). As seen in Figure 3, the availability of the solar energy can be used to prioritize the sites for renewable energy development. Some literatures claim that the eastern parts of Indonesia are exposed more solar irradiation than the western part, but the results here indicate that the reported solar energy potential distribution is only partially true. Some of the western were found, *i.e.* south Sumatera, south Kalimantan (Borneo) and Java island, and mid-eastern parts of Indonesia, *i.e*. Bali, East and West Nusa Tenggara, South Sulawesi, have the most stable annual solar-energy potential.

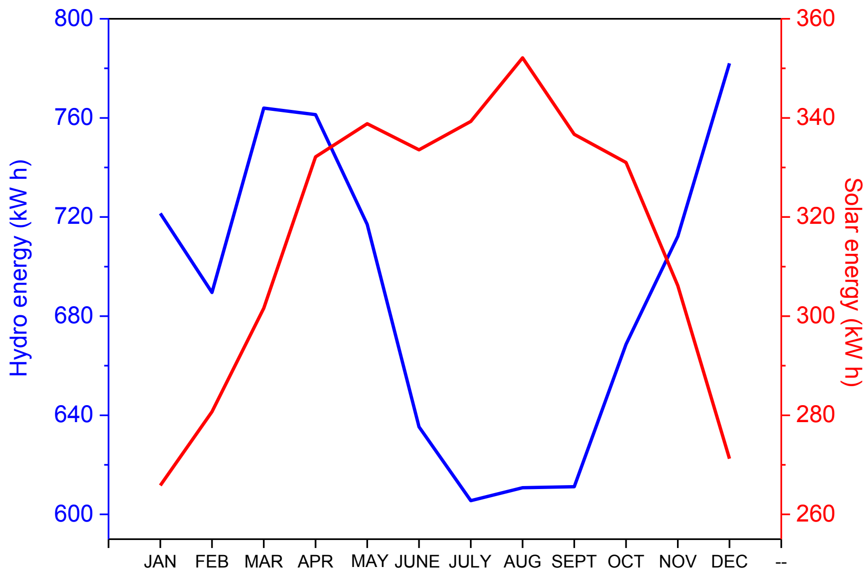


Fig. 4. Monthly potential energy output for hydropower and solar power generation at national level.

The monthly hydro and solar energy potential at national level is shown in Figure 3. It can be clearly seen that the hydro energy potential is lower ((620 ± 10) kW h) during the dry season (approximately starting from May to October), and in contrary the solar energy potential is at the highest level ((335 ± 5) kW h)) during the dry season. Overall, the results show that seasonal variation is not the case for solar energy potential in Indonesia, whilst the hydro energy potential is slightly affected by the seasonal change. Taking the integral of each renewable energy potential in a year, the dry to wet season ratio of total energy for hydro and solar energy is 42 : 58 and 54 : 46, respectively.

Table 1. Hydro and solar energy potential at provincial level during the wet and the dry season.

Province	Hydropower (kW h)		Solar power (kW h)	
	Wet	Dry	Wet	Dry
Aceh Darussalam	7 780	5 168	300	293
Bali	1 133	875	399	491
Bangka Belitung	108	92	295	373
Banten	1 595	1 219	313	436
Bengkulu	2 390	2 129	299	351
Central Java	1 663	1 377	333	436
Central Kalimantan	5 664	4 008	281	361
Central Sulawesi	7 219	5 714	302	345
East Java	1 310	1 013	374	492
East Kalimantan	12 791	9 021	280	337
East Nusa Tenggara	2 510	1 518	355	466
Gorontalo	3 698	2 707	307	317
Jakarta	515	368	317	451
Jambi	3 487	2 976	295	338
Lampung	1 614	1 313	305	387
Maluku	2 895	1 654	301	291
North Maluku	1 862	1 279	317	288
North Sulawesi	2 859	2 289	321	307
North Sumatra	4 980	3 526	336	335
Papua	18 348	10 901	245	251
Riau	2 452	1 965	305	331
South East Sulawesi	4 788	3 186	330	398
South Kalimantan	1 813	1 519	288	381
South Sulawesi	7 760	6 288	306	380
South Sumatra	1 725	1 468	301	365
West Java	2 531	2 303	329	427
West Kalimantan	5 412	3 713	283	356
West Nusa Tenggara	1 413	818	331	423
West Papua	6 491	3 825	260	256
West Sumatra	3 877	3 398	313	334
Yogyakarta Special Region	1 571	1 302	310	397

The hydro and solar energy potential distribution in provincial level is listed in Table 1. The results above support the current government action plan, for example the establishment of solar energy power plant in Nusa Tenggara. In fact, East Java shows promising solar energy to harvest but the availability of area for PV power plant limits the development of large PV system. The levelized cost of (renewable) energy utilizing hydro and solar energy is comparable with the electricity price from PLN. Kumara et al [20] reported that the micro-hydropower plant built in Bali allows the consumer to afford electricity with reasonable price of USD 0.5 per kW h. Furthermore, the use of off-grid PV systems is considered cheaper and profitable than generating electricity by using diesel generator or hybrid diesel/PV system.

4 Conclusion

In this paper, the potential of hydro and solar energy in Indonesia is mapped for predicting off-grid system utilizing renewable energy resources. The present results highlight the seasonal variation of hydro and solar energy potential in Indonesia and show that solar energy potential in Indonesia is stable throughout the year. The hydro energy potential enables mostly the development of hydropower plant in the scale of pico to minihydro. Meanwhile, the solar energy distribution reported here presents a higher and more stable energy potential in Java island, particularly in East Java, than in eastern part of Indonesia which is partially different to the literature. This implies that a thorough calculation and estimation is required for future revised solar energy map.

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