Assessing Solar and Wind Energy Technical Potential using GIS Approach: A case study in Sumba Island, Indonesia

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Abstract
Rural areas with low density and scattered population usually suffer from low infrastructure, such as electricity which results in poverty. Sumba Island is a case in which it lacks public infrastructure, due to scattered population. Sumba Island has low economic activities as well as scattered population distribution which makes electrical company difficult to develop grid network. Nevertheless, studies show that this island has abundant renewable energy (RE) potentials. This study aims to assess the estimated technical potential from photovoltaic (PV) and wind energy to provide technical knowledge for investor to encourage their participation in achieving Sumba Iconic Island goals for 100% RE powered island. Geographic information system (GIS) approach was used to estimate available area by setting several criteria based on topographic and land-use conformances. Technical potentials were then estimated based on available areas, RE resource and also technological limitations. The results showed that the study area has notable potential of PV at 7,913 GWh/year and fair potential of wind at 794 GWh/year. Available area for PV can be found almost everywhere, but high wind speed sites only exist in Kamanggih, Lai Mbonga and Kambata Bundung villages. The results suggest that the big potentials of PV and wind turbine can be deployed to electrify scattered rural communities.

Keywords: Sumba Iconic Island, Solar, Wind, GIS, Technical Potentials of RE

Introduction

Sumba Iconic Island (SII) is a multi-stakeholders initiative aimed to create a role model for 100% RE electrified island in Indonesia. It was started in 2010 by Ministry of Energy and Mineral Resources, State Ministry of Development Planning and HIVOS (an international NGO) which envisioned to increase RE penetration in Indonesia as well as to strengthen the commitment to reduce carbon dioxide emission (NREEC, 2012).

Sumba has been chosen as the ideal candidate because of its unique characteristics, such as low access to modern energy but storing big potential of RE. A study conducted by WinRock (2010) uncovered significant potential of RE in Sumba. The identification of several waterfalls in Sumba results in nearly 4.5 mega-watts (MW) hydroelectricity potentials. In addition, WinRock also visited three sites with notably good wind speed. The wind speed ranges from 5 to 9 m/s and it is estimated to have potential greater than 200 MW. Solar energy potentials also existed in Sumba with daily solar insolation of 5 kWh/m^2/day (kWh is kilo-watts/hour).

As part of the strategy to achieve the Sumba Iconic Island goals (HIVOS, 2014), research and development of RE related topics are encouraged. RE technical potential which represents the achievable energy generation after considering topographical, land-use, and technological constraints is expected to establish an upper-boundary estimate of development potential (Lopez, Roberts, Heimiller, Blair, & Porro, 2012). Several studies have been done to assess the RE potential in several countries, such as in USA (Dahle, 2008; Doris, Lopez, & Beckley, 2013; Lopez et al., 2012), Japan (Wakeyama & Ehara, 2011) and Taiwan (Yue & Wang, 2006).

The uses of GIS techniques in RE planning have benefits for collecting and elaborating all required information in order to make decision. The GIS tools enable users to perform spatial analyses through digital representations of geographic area, combined with other geographically referenced information (Pellegrino, Caiaffa, Grassi, & Pollino, 2008). Therefore, it can be used to efficiently estimate RE technical potential over wide areas.

Methods

The assessment of RE technical potential mainly considers land-use and topographical constrains and system performance of each RE technology. In this study, solar and wind energy technical potential were assessed using two different steps:

1. Evaluating topographical and land-use constraints
2. Estimating the electricity output based on technological constraints.

The first step is to evaluate the topographical and land-use constraints. The output of PV system and wind turbine highly depends on the shading effects on PV panels or variation of the wind speed which is immensely affected by geographic features of the site. The geographic analysis on site suitability for PV and wind was focused on terrain slope and conformance of the land-use (Table 1).

Space Radar Topography Mission (SRTM) Digital Elevation Model (DEM) data with 90 m spatial resolution was used to perform terrain analysis (USGS, 2004). Slope map was generated using spatial analysis tool in ArcGIS. In addition, the land-use map from Indonesia-Geospatial Portal (http://portal.ina-sdi.or.id/) was used for further analysis to exclude non-suitable land-use type to certain buffer.

Table 1. Summary of criteria for topographical and land-use constraints.

Criteria	PV System	Wind Turbine
Topographic constraints	▪ Slope less than 5%	▪ Slope less than 20%
Land-use exclusions	▪ Residential areas with 50 m buffer ▪ Water body with 50 m buffer ▪ Wetlands with 50 m buffer ▪ Forest with 100 m buffer ▪ National parks or protective forests with 300 m buffer	
Resources constraints	▪ N/A	▪ Wind speed at hub height ≥ 3 m/s

The next step is estimating electricity output based on system performance. Due to different characteristics of RE resources, detailed explanation for estimation of PV system and wind turbine electricity generation will be discussed in the separated parts.

Solar energy

Solar energy resource over suitable areas (after performing topographical and land-use assessment) is assumed to be uniform. Therefore, electricity output was calculated based on available areas from previous step, using several assumptions. PV capacity factor (*Cf*) are conservatively assumed at 14% as suggested by IRENA (2015) and Meier (2015). Whereas power density was assumed at 0.048 kW/m^2 (Lopez et al., 2012). The equation for annual electricity generation from PV is as follow,

$$E_{pv,ann} = A_{pv} \times Cf \times PD_{pv} \times 8760 \quad (1)$$

where $E_{pv,ann}$ is annual solar energy potential (kWh/year), PD_{pv} is power density (0.048 kW/m^2).

Wind energy

The wind speed data was gathered from the NREL Wind Resource Assessment Program (Elliott, 2002) which is also available at IRENA Global Atlas[1]. It gave the wind speed class map (with information of wind speed range) at 30 m height along with its Weibull parameters. Nevertheless, this map should be interpolated to get the average wind speed at designated height (12 m). The wind speed interpolation technique was used following wind profile power law formula (Bailey, McDonald, Bernadett, Markus, & Elsholz, 1997),

[1] IRENA Global Atlas is an initiative to boost RE development by providing spatial data on RE resources, including solar energy, wind energy, bio energy, and geothermal energy along with marine energy (http://globalatlas.irena.org).

$$v = v_r \left(\frac{z}{z_r}\right)^{\alpha} \quad (2)$$

where v is the velocity at designated height z (m/s), v_r is the scaling velocity (reference velocity) (m/s), z_r is the reference height (m), α is wind shear exponent which may vary according to the type of terrain and surface roughness features (Olsen & Preus, 2015). In this study, the wind shear exponent will be based on land-use and terrain type (Table 2).

Table 2. Wind shear exponents based on land-use type (Olsen & Preus, 2015).

Land-use type wind shear	Exponent α
Agriculture	0.30
Dry forest	0.45
Lake	0.20
Plantation	0.35
Residential	0.31
River	0.20
Swamp	0.25
Shrub	0.30
Savanna	0.25

Electricity output from wind turbine depends on wind speed distribution throughout the year and power curve for specified wind turbine. Weibull distribution is used to get distribution of the data (Wakeyama & Ehara, 2011),

$$f(v) = \frac{k}{\lambda}\left(\frac{v}{\lambda}\right)^{k-1} e^{-(x/\lambda)^k} \quad (3)$$

where $f(v)$ is in percentage of occurrence of wind speed at v m/s, k is the Weibull k factor, λ is a function of k and average wind speed using gamma distribution.

In addition, TECO H3000 wind turbine was chosen to estimate the power output. It has the capacity of 3 kW with rotor diameter of 4.2 m and hub-height of 12 m. The power curve can be used to estimate the power output at specific wind speed (Figure 1). Estimated energy production was calculated using this formula,

$$E_{wind,ann} = \sum_{v=0}^{20}[f(v)p(v)8760] \quad (4)$$

where $E_{wind,ann}$ is annual electricity output from each wind turbine, $p(v)$ is the power output (W) at specified wind speed (Wakeyama & Ehara, 2011).

Required area for each wind turbine was calculated using 5 D x 10 D (D is rotor diameter) configuration (Irizarry-Rivera, O'Neill-Carillo, Colucci-Ríos, & de Asuntos Energéticos, 2009). Each wind turbine will be placed apart a distance of 10 D in the direction of prevailing wind and half of that separation in the direction perpendicular to the prevailing winds. Using TECO H3000 wind turbine with 4.2 m diameter, the required areas will be 882 m^2. Then, using available area from previous step, number of wind turbine or total capacity of wind farm can be calculated.

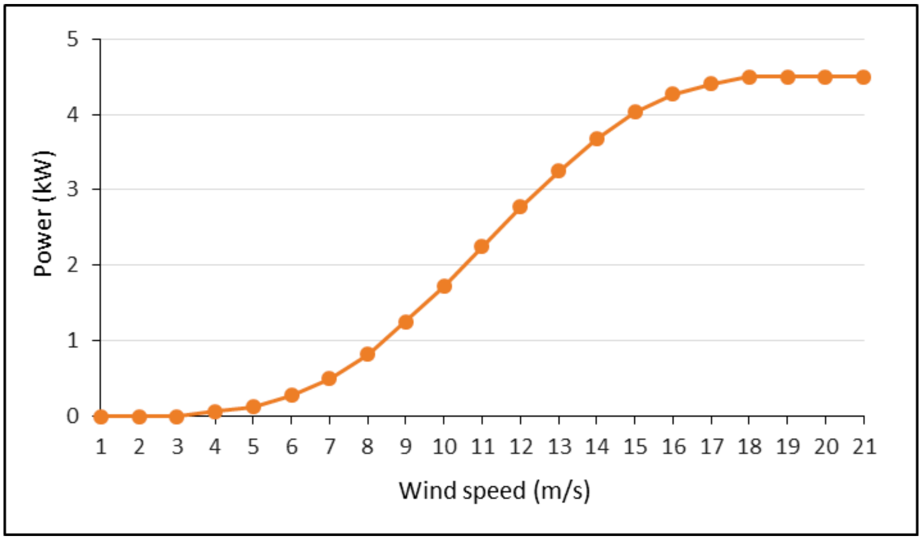


Figure 1. TECO H3000 power curve.

Results and Discussions

Study area

This study was conducted for the area of Kahaungu Eti sub-district, East Sumba, Indonesia (Figure 2). It has 9 villages spanning over 417.92 km^2 area with total population of 8,339 people (1,866 households). The settlement condition in Kahaungu Eti is scattered rather than clustered because Sumbanese tend to live within their tribes near their farms. Therefore, it is difficult for utility company to connect these villages to the central grid due to high inter-households distribution cost.

In general, almost all villages in Kahaungu Eti lack electricity infrastructures. Only in the capital of Kahaungu Eti, Kamanggih village, the Government has built public infrastructures, including isolated grid with 55 kW diesel generator as the main power plant. Following SII project, the Ministry of Energy and Mineral Resources has distributed small solar lighting system for each household. However, due to poor quality and lack of after-sales service, most products are failed before the first six month (JRI, 2013).

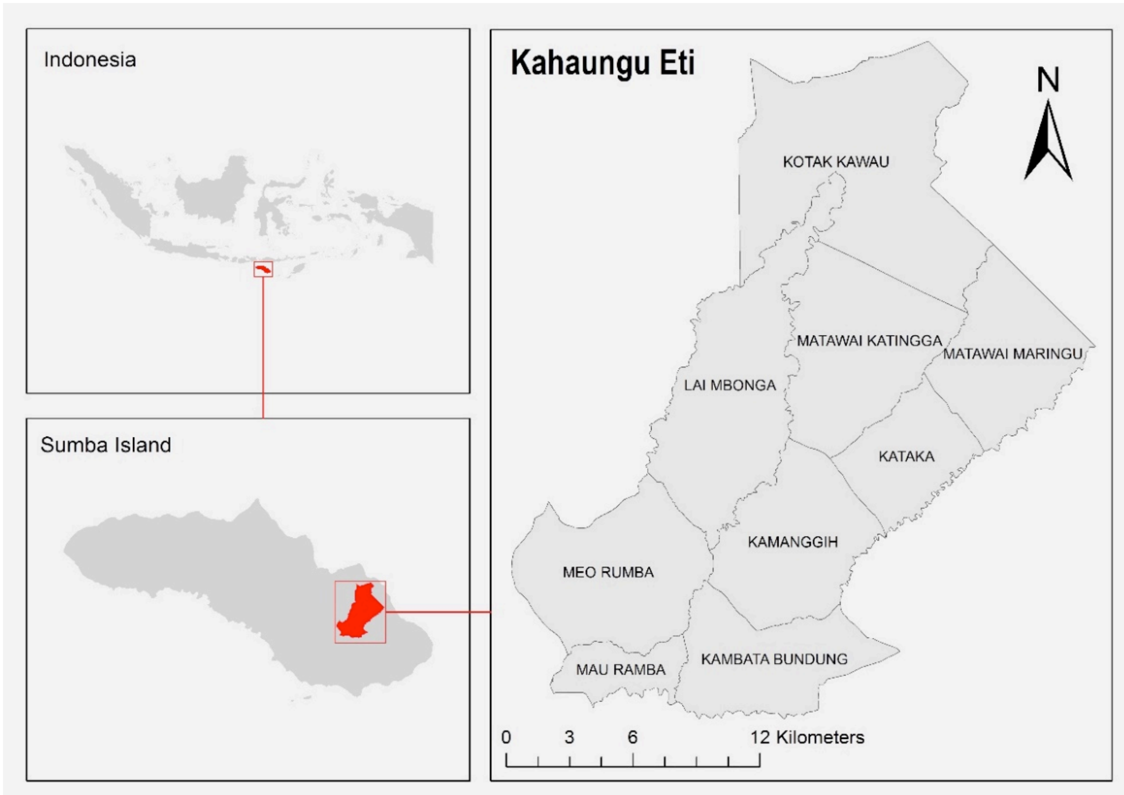
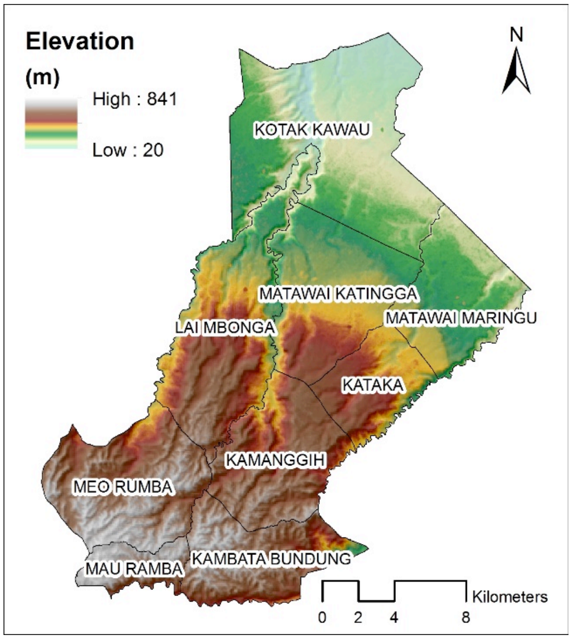


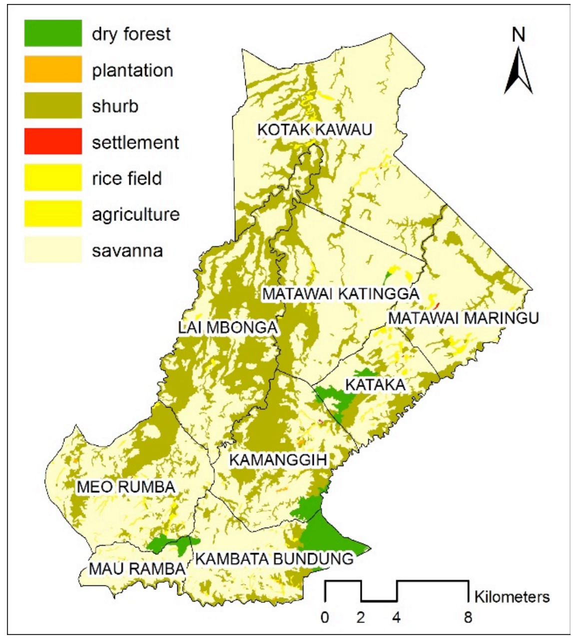
Figure 2. Study area of Kahaungu Eti sub-district

Southern part of Kahaungu Eti sub-district, especially in Meu Romba, Mau Ramba and Kambata Bundung villages are located on higher elevation and generally have mountainous topographic profiles. Steep terrains are found almost everywhere. Therefore, suitable areas from solar PV installation are very limited.

In addition, most areas in Kahaungu Eti sub-district are covered by dry grass savanna. There are two protective forests namely Luku Melolo in Kataka village and Lulundilu in Kambata Bundung. There are also small areas of settlements and waterbody. These protective forests, settlements and waterbody do not comply with solar and wind farm land-use requirements and therefore they were excluded from the RE potential map. Buffer zones were also applied with certain distances following different land-use types in order to further ascertain the land suitability for solar and wind potential map.



(a)



(b)

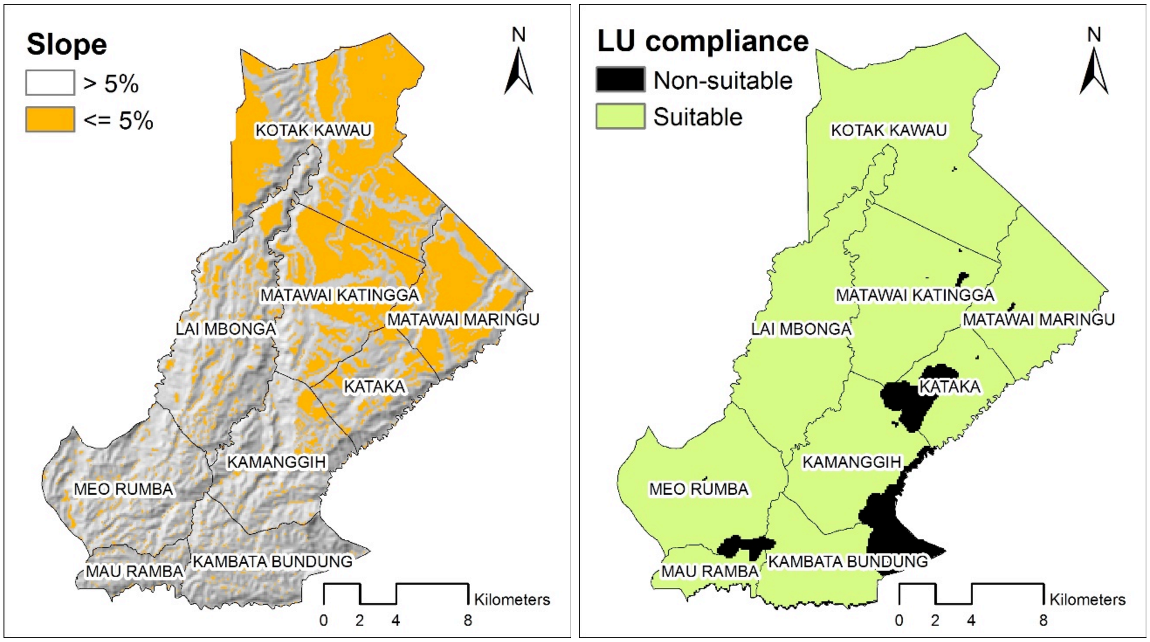
Figure 3. Local conditions of study area: (a) elevation map and (b) land-use map

Solar energy potential

Solar energy potential was calculated based on suitable area by firstly considering slope threshold and land-use compliance. The 5% threshold was applied and results in less available area in Southwestern part of Kahaungu Eti. In addition, buffer zone around protective forest also significantly removes some areas from solar potential map.

Villages located on the northern part generally have larger area available (Figure 4), such as Kotak Kawau (58.47 km^2), Matawai Katingga (26.8 km^2) and Matawai Maringu (24.23 km^2). The rests have available area of less than 10 km^2. Mau Ramba has the smallest area available with only 0.63 km^2. The limited availability of areas for PV are mostly attributed with mountainous terrain.

Solar energy potential per village is shown in Figure 5. It represents aggregated annual electricity production from PV on the areas within each village. The highest solar potential can be found in Kotak Kawau village with annual electricity production of approximately 3,870 GWh. It is followed by Lai Mbonga, Matawai Katingga and Matawai Maringu which are located in the central of Kahaungu Eti with annual production between 1,000 and 2,500 GWh/year. Less electricity production are found in Meo Rumba Kamanggih and Kataka while the least potential are found in Kambata Bundung and Mau Ramba.



(a) (b)

Figure 4. Analysis of topographic constraint (a) and land-use compliance (b)

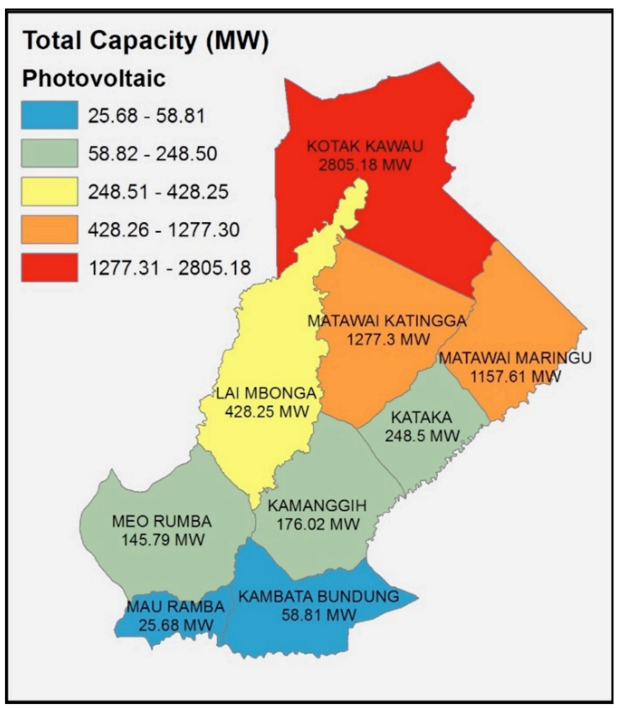


Figure 5. Estimation of total generating capacity for PV for each village.

At village level, annual electricity production from solar energy gradually decrease towards south where the elevation is higher and the topographic is mountainous. Therefore, this area is not suitable for PV installation. In addition, villages in the northern parts have larger areas, which can be seen on Table 3.

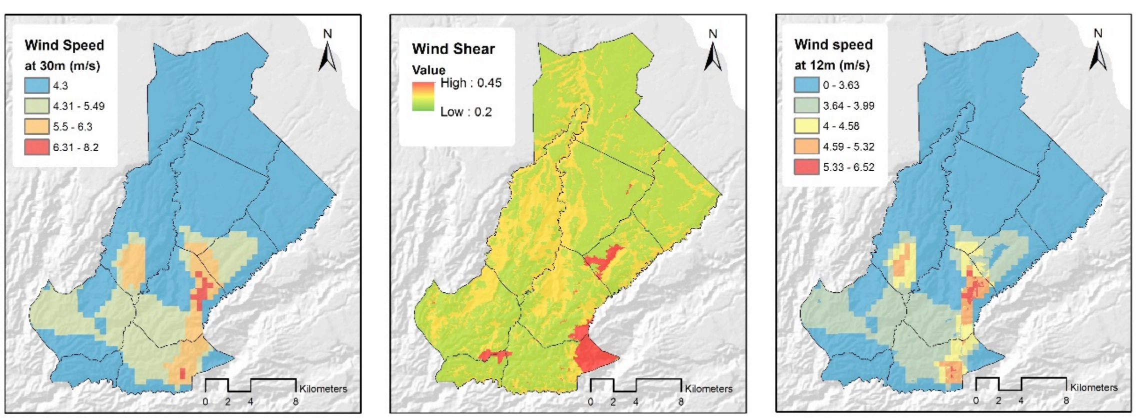
Table 3. Available areas, generating capacity and annual electricity production for solar energy for each village.

Village	Available area (km^2)	Capacity (GW)	Estimated output (GWh)
Kamanggih	3.7	176	215.9
Kambata Bundung	1.2	59	72.1
Kataka	5.2	249	304.8
Kotak Kawau	58.4	2,805	3,440.4
Lai Mbonga	8.9	428	525.2
Matawai Katingga	26.6	1,277	1,566.6
Matawai Maringu	24.1	1,158	1,419.8
Mau Ramba	0.5	26	31.5
Meo Rumba	3.0	146	178.8

Wind energy assessment

Sumba is considered as area with good wind resources. Based on wind speed map from NREL wind resource assessment program, the average wind speed in study area ranges from 4.3 to 8.2 m/s at 30 m height (Figure 6). Nevertheless, higher wind speed sites are only available in Lai Mbonga, Kamanggih and Kambata Bundung. The rest area has fair average wind speed.

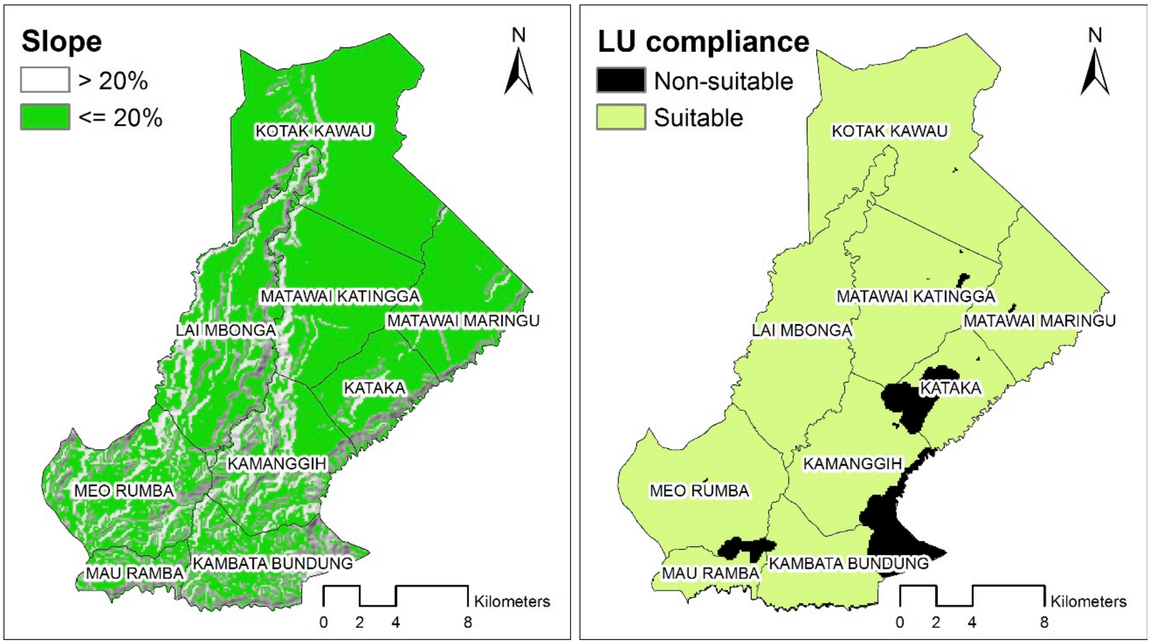
TECO H3000 wind turbine with capacity of 3 kW was used to calculate the electricity output from the wind turbine. This wind turbine is able to generate up to 4.5 kW at 17 m/s wind speed. As the wind turbine hub is at 12 m height, the wind speed map should be adjusted as well. Following different wind shear exponent from various land-use type, wind speed was interpolated. The results show that the average wind speed at 12 m height varies from 3 m/s to 6.5 m/s.



(a) (b) (c)

Figure 6. Wind speed map adjustment: (a) wind speed at 30 m height, (b) wind shear exponent and (c) wind speed at 12 m height.

For topographical and land-use constraint, the same process as the solar energy assessment was also implemented, except the slope threshold was set at 20% as suggested by previous study (Lopez et al., 2012). It results in significantly more areas available for wind turbine installation (Figure 7).

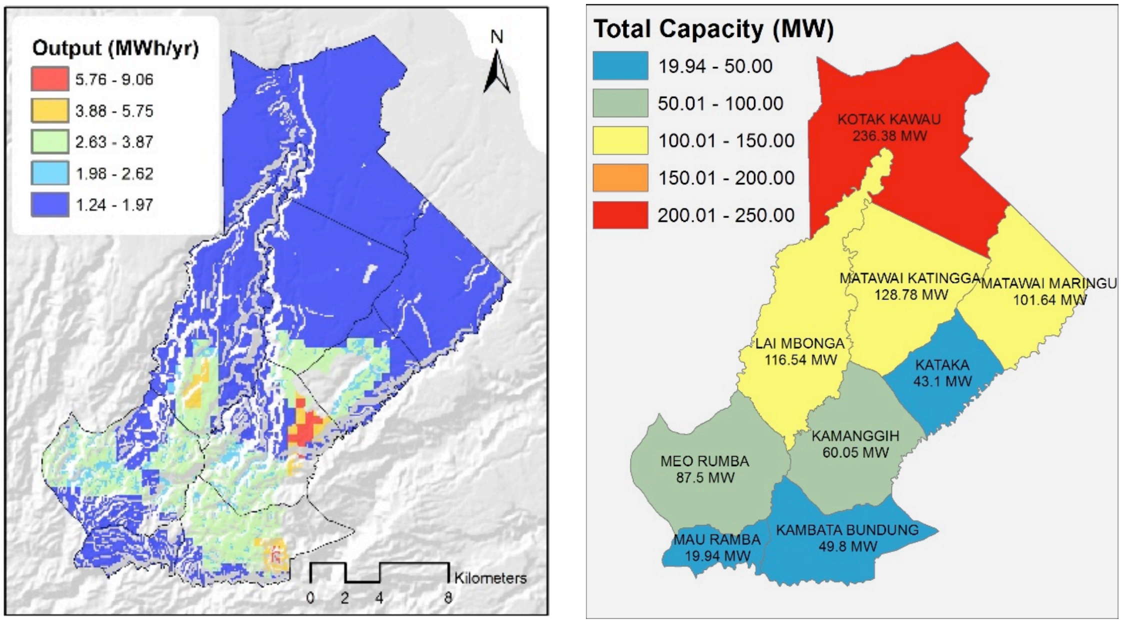


(a) (b)

Figure 7. Suitable areas for wind farms: (a) slope classes and (b) land-use constraints.

The estimated output of wind turbine varies by its wind speed (Figure 8a). It ranges from 1,235 kWh/year for sites with the average wind speed of 3.12 m/s to 9,060 kWh/year for sites with the average wind speed of 6.52 m/s. As the wind speed variation affects the electricity production output, the capacity factor (*Cf*) for each sites with different wind speed are also different. TECO H3000 has rated capacity of 3 kW at 11 m/s. However, the maximum power can reach up to 4.5 kW at 17 m/s. Therefore, the *Cf* is up to 34%.

The aggregated electricity production from wind turbine per village can be seen at Figure 8. The highest annual electricity production can be found in Kotak Kawau village with 127.5 GWh electricity production per year from 236.4 MW generating capacity. The lowest potential can be found in Mau Ramba with only 10.8 GWh/year electricity production. However, electricity generation can be higher with less generating capacity in some villages, especially in the areas where the average wind speed is more than 5 m/s. For example, total wind farm capacity in Kamanggih is 60 MW but it can generate up to 59.3 GWh/year which is slightly higher than electricity generation in Matawai Maringu (54.8 GWh/year) with capacity of 101.6 MW.



(a) (b)

Figure 8. Wind energy potential: (a) Estimation of electricity output for each 3 kW wind turbine and (b) Total wind farm capacity for each village.

Table 4. Available areas, generating capacity and annual electricity production for wind energy for each village.

Villages	Available Area (km^2)	Capacity (MW)	Estimated output (GWh/year)
Kamanggih	21.6	60.0	59.3
Kambata Bundung	17.9	49.8	45.0
Kataka	15.5	43.1	29.7
Kotak Kawau	85.0	236.4	127.5
Lai Mbonga	41.9	116.5	74.5
Matawai Katingga	46.3	128.8	73.5
Matawai Maringu	36.5	101.6	54.8
Mau Ramba	7.2	19.9	10.8
Meo Rumba	31.5	87.5	62.1

Renewable energy technology comparison

In general, Kahaungu Eti has good potential of both solar and wind energy. Solar radiation in the study area ranges around 5 kWh/m^2/day which is considered as good. On the other hand, the average wind speed in the study area ranges from 4.5 m/s to 8.2 m/s at 30 m height, even though windy sites are only available in several villages. In addition, as this sub-district is considered as rural areas with less residential areas and mostly covered by savanna, there are still wide areas to install these two RE technologies.

Nevertheless, when considering annual electricity output, there is a significant difference between solar and wind energy. The total annual electricity production for solar energy in Kahaungu Eti was estimated to reach 7,913 GWh/year whereas the estimated electricity production for wind energy is only 793 GWh/year or about 10% of annual production of solar energy. The low electricity production from wind turbine might be associated with low capacity factor of small scale wind turbine. In addition, if electricity production per specific unit area was considered, solar energy is superior with around 59 GWh/km^2 compared to wind energy with only 1.9 GWh/km^2. It means that wind turbines require larger areas to produce the same amount of electricity output from PV.

The selection of small scale wind turbine in the analysis is related to economic activity in the study area which is relatively low (Castlerock, 2014). When there are only few industries and small shops, the demand becomes low as well. In addition, central grid does not exist in the study area. Previously, there was only 55 kW diesel generator operated under isolated grid configuration to power the whole Kamanggih village. Now, there are operating micro hydro power plant and also small scale wind farm (IBEKA, 2011; Pertamina, 2013).

Even though both technologies are found to be potential in the study area, they have intermittency characteristics which may become the bottleneck in electricity planning associated with balancing supply and demand (Mohammed, Mustafa, & Bashir, 2014). For example, solar radiation at Kelurahan Kambajawa, Kecamatan Kanatang is relatively constant throughout the year (WinRock, 2010). However, electricity from PV is only available during the night. Therefore, battery is essential for complementing PV system. On the other hand, electricity from wind turbine might be available during the day and the night but it has seasonal pattern. For example, observation station in Hambapraing shows that wind speed in that area is usually high during summer (between May to August) and low during winter (from November to March) (Hirsch et al., 2015). Therefore, in any off-grid or mini-grid system using these technologies, energy storage should be attached to ensure its reliability.

Conclusion

Sumba island, especially in Kahaungu Eti sub-district, has considerably good potential of solar and wind energy. Solar radiation is relatively constant throughout the year around 5 kWh/m^2/day while average wind speed on the study area are between 4.5 and 8.2 m/s. Solar and wind energy technical potential was assessed using GIS approach to further account achievable energy generation.

Suitable areas for solar or wind farms are limited with steep terrains and non-suitable land-use type and its buffer zone. Some areas are mountainous and too steep (especially in Southern part of Kahaungu Eti) so that they are not suitable for solar and/or wind energy installation. Northern part of study area has more flat areas which allow more PV and more wind turbines to install. Accordingly, Kotak Kawau has the largest capacity and the highest annual electricity production from both solar energy and wind energy system at village level.

Especially for wind energy potential, electricity output is highly influenced by average wind speed. In windy sites a wind turbine can generate more electricity. Therefore, wind turbine installation should consider high wind speed sites because smaller capacity of wind farm requires less investment.

In this study, electricity production from solar energy is estimated to be far away higher than electricity production from wind energy, due to the use of small-scale wind turbine. Considering the demand and suitability for the study area, small-scale wind turbine was chosen as reference to estimate annual electricity production from wind turbine. In addition, this small-scale wind turbine requires wide areas to install but does not deliver enough electricity.

However, both technologies have intermittency disadvantages. Therefore, energy storage should be included in the system. Furthermore, as the area is not constraint in the study area, the selection of RE technology should also be based on installation and maintenance costs.

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