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Research Article **EAI.EU**

Investigation of Sustainable Technology Options: Wind, Pumped-hydro-storage and Solar potential to Electrify Isolated Ziway Islanders in Ethiopia

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Abstract

This research at supplying electricity to Ziway lake islanders in Ethiopia through studying the wind, pumped hydro-storage (PHS), and solar energy potentials. A wind mast is erected, and measurements at 10,50 and 70m heights are taken for a year long. The wind is of class-4 with wind speeds of 7m/s at 50m, and 7.87m/s. The energy density is 318.8 kWh/m^2 (50m). GIS-based 3D digital elevation model (DEM) is used to investigate the PHS, with the lake as lower-reservoir and a dried-out crater pond of an extinct volcano as upper reservoir. The head is extracted using optical remote sensing technology, DEM(LiDAR) 12.5m. Constraints considered are topography, area, head, and slope. Twelve upper reservoirs are identified within head range of 50-250,50-200, and 50-100m. The results showed a PHS capacity of 5976 KWh at head of 60m can be developed. The solar energy potential is 6.1KWh/m^2 /day. The finding proved the viability of electricity supply to the community.

Keywords: Ethiopia, GIS, DEM, Pumped hydro-storage, Sustainable Island, WED

Received on 22 March 2022, accepted on 31 July 2023, published on 01 August 2023

doi: 10.4108/ew.88

1. Introduction

Dependence on traditional energy poses a risk to the health of society and the eco-systems. Additionally, the fossil-based energy supply systems are one of the highest CO_2 emitters globally. Unless timely steps are taken to decarbonize the energy sector, the world may not be able to achieve the goals set in the series of submits such as the latest Paris Agreement, and the UN-energy goal7 [1-8].
Access to economical, consistent, and sustainable energy sources can have a transformative impact on productivity, incomes, etc. thereby changing livelihoods of a society. In sub-saran Africa around 600 million people and in Ethiopia, based on estimated value for the first half of 2020, around 53 million are lacking secured energy, typically in remote areas [9-11].Ethiopia is listed within the top 20 countries of highest electricity access deficit. Less than 5% of its population use clean energy technologies as a primary means, about 95% depend on traditional biomass for cooking and other purposes. The country faces energy challenges in different fronts: growing economy in the past few years, lack of modern energy access to its more than 50% population, sustainability of the export of electricity to the neighbouring countries, etc. [12].

Scholars have explored the role of Eco-friendly energy sources in reducing socio-economic problems, promoting equity, healthy living conditions, a prosperity of a given nation, and boosting power supply to meet the ever-increasing energy need of the universe sustainably[13-17].These circumstances have raised an extensive interest in low-carbon energy development for many years. In line with this, African leaders have decided to support relevant international policies, i.e. eliminating the greenhouse causing carbon from the energy sector to keep the average temperature below 2^{o}C and providing modern(green) energy and services [18]. In the case of Ethiopia, the process of transforming Ethiopia's industrial sector as the main driver, the government has an ambitious plan of boosting the contribution of the modern energy in the national energy-balance to a significant portion by 2030, i.e., 22 GW from

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hydro, 7 GW from wind, and 1 GW from geothermal. This is in line with the ambition of becoming a middle-income country by 2025 [19-21]. Accordingly, the development of Eco-friendly forms of energy is increasing from time to time as indicated in Figure 1.

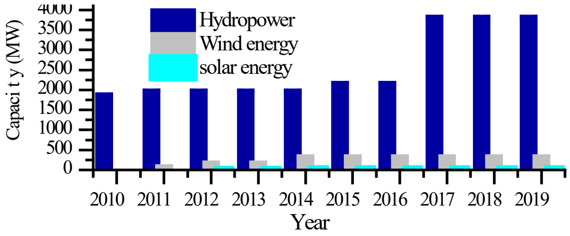


Figure 1. Renewable-energy capacity installed until the end of the year 2021 in Ethiopia [22].

The ultimate goal of this research is to provide input to the ambitious goal of the country by addressing electricity access deficit at a specific region in the country and that region is the Ziway islands. This is in addition to giving electricity to an estimated population of well over 5000 residents in the islands. The economic situation of the country is one main reason for not reaching this people with electricity, and it seems to be so for not anytime soon. Islanders fulfil their energy demand from traditional and non-renewable energy sources. These include imported fuels (diesel & kerosene) for irrigation and lighting, solid-biomass (fire-wood and Animal dung) for baking and cooking, and battery(dry-cell) for playing music and radio. Islanders are engaged mainly in subsistence agriculture and fishing Figure 2. The natural vegetation is the major source of fuelwood that placed pressure on the vegetation and biologically precious resources of the islands. According to the interview results one of the tiresome and time-consuming tasks of the women is grinding the raw grain for flour by hand, which otherwise they have to take it several miles away on foot and crossing the lake by boat to the town (Ziway) in search of grinding mills. Even if the location of the inhabitants is blessed with different eco-friendly energy sources, like solar, wind, and pumped hydro-power, there is no action taken till now in utilizing these resources to improve the living standard of the community [23].

Figure 2.Community activities of the Islands

It is to be noted that Ziway is one of the lakes lying in the rift valley. There are mainly five volcanic islands in the Lake. People inhabit three of the islands namely, Tulugudo, Funduro & Tedecha (the focus of this study) Figure 12. Over 3,000 peoples reside in Tedecha, 2,400 in Tulugudo, and about 100 in Funduro. Fishing from the lake is common for subsistence but without preservation, as there is no refrigeration.

2. Materials and Methodology

2.1. Literature Reviewed

Many previous studies used GIS methods to find suitable locations for PHS. One of these is where 31 European countries were examined for a potential of pumped hydropower energy storage. The study is based on two existing reservoirs of hydropower and water-supply projects. They used 90 and 250 m DEM and land use as input datasets [24].The investigation could have included the ranking metrics to be complete.

Another study [25] investigated the possibility of modelling two locations with different site structures called the dry canyon and the turkey nest and developed several GIS based algorithms to enable automated site search inputs. Accordingly, the study identified 168 dry canyons and 22 turkey nests with a storage capacity of 276 GWh. This study is limited to the two sites dry-canyon and turkey nest. Yet, another study [26] focuses on the assessment of the potential for small PHS, as a contribution to the stability and reliability of the grid. A generic method is developed, which is capable of evaluating global PHS storage capacity on a large scale. In the study, the surrounding topography has been used to calculate the storing capacity of a water battery. France is considered as a test case. The results showed small PHS potential ranging from 14GWh, if only existing lakes are taken into account, to 33GWh, if lakes and sinks with a minimum storage capacity of (500kwX10h) are taken into consideration. The identified locations are sorted according to the virtual energy costs. Lu, X. and S. Wang [27]examined existing lakes and valleys with the aim of developing large-scale (> 500 m) PHS. In their investigation, they used stream lines and the location search is done at a distance of 500m.

It can be argued that the above studies extracted the elevation information using (DEM) from Shuttle Radar Topography Mission (SRTM) data. DEM affects terrain modelling due to the different elevation extraction techniques such as SRTM, USGS (US Geographical Survey), Space borne Imaging Radar, etc. These differences can potentially lead to better analytical results when used to investigate local problems. Understanding these differences and the potential defects are required prior to analysing change detection in order to incorporate the inherent uncertainties into analysing the topographical change. Because of this, this study relied on DEM LiDAR's tool to extract the elevation information with a resolution of 12.5m by taking into account the proximity of the community and the suitability of the upper reservoir for small-scale farming (Energy Nexus Food). Gravity is to be used for irrigation on the island's gentle slope. According to [28], the generation of DEM data with the LiDAR system has several advantages over other models, i.e., it can measure the soil surface in overgrown and urban areas more reliably and more responsively compared to others.

The authors believe that so far, at least in Ethiopia, there has been no published scientific work with this method to assess a potential for PHS. Therefore, this study would serve as a methodological reference for further work by researchers and policy makers locally or at the regional level in East Africa and/or elsewhere. It should also be noted that there are numerous potential locations locally for PHS that can be developed for a stand-alone and/or hybrid power generation application. Regarding the solar and wind energy potential, there have been a number of studies previously done [23, 29-33]. However, the data used in the studies can be said were not good enough for research purposes, as the data in the time were meant for either agricultural purposes or weather forecast. Even at the present time there is no, as such, good enough data that is well organized and documented in the concerned governmental offices. Hence, here, in this study, for the solar energy, it is sunshine-hours data that is used to scientifically manipulate and come up with a plausible solar radiation potential of the region. And for wind, actually measured data over a period of one year is used by erecting wind mast and installing data logger. The measurements were recorded at every ten minutes' elapses for a whole of a year. Not only that, but the data is also compared against international data sources such as NASA. This study also differs from the previous other works [34-36] which used a standard deviation method to decide the shape(k) and scale factor (c), in that we applied the least-squares method to analyse the distribution of wind.

2.2. Wind speed measurement and data processing

As mentioned earlier, data is collected through field measurement by erecting wind mast at the site shown in Figure 3 (a). The measurements are taken every ten minutes for a year, from 2017 to 2018, at heights of 10, 50, and 70 m height, as shown in Figure 3 (b). Also, for comparison reasons, wind speed data and direction from NASA database has been considered. Data from NASA is measured at an interval of one-hour and at a height of 50m. The data to be used for the design of the hybrid system is that of the 70 m height.

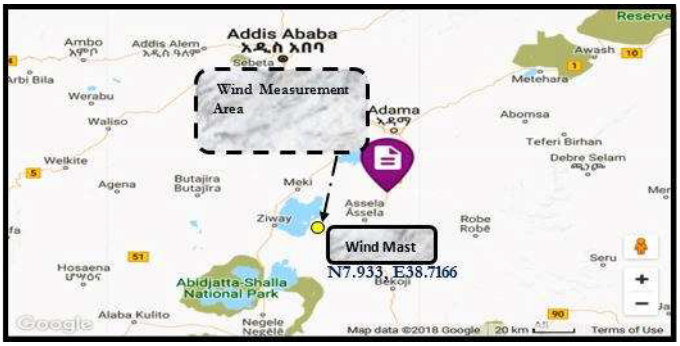
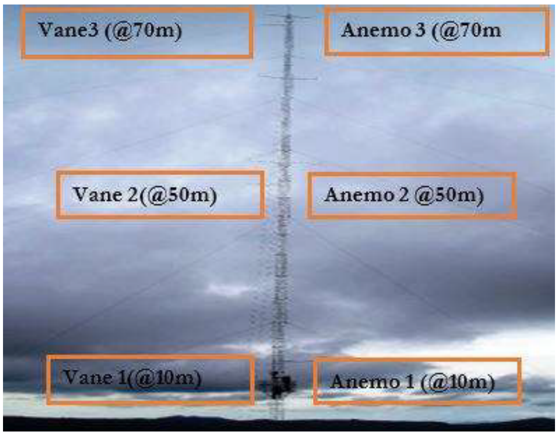


Figure 3. Data Measurement area (a)

The overall wind power potential determination followed the established conceptual framework dissipated in **Figure 4** [44].where:- V(av): average wind speed, WSV: wind speed variability, WsH: wind speed at different heights, WS: wind statistics, An(EP) annual energy production, WPD: wind power density, PDF,CDF (probability and cumulative density function of the wind in the region.



Wind Mast setup (b)

2.3. Wind Energy Modelling

In many studies [34, 36-41] the wind speed frequency is closely approximated by the Weibull distribution function:

$$f(v) = \frac{k}{c}\left(\frac{v}{c}\right)^{k-1} \exp\left[-\left(\frac{v}{c}\right)^{k}\right]. \qquad (1)$$

Where: v = wind speed (m/s), k = the shape factor & c = the scale factor (m/s)

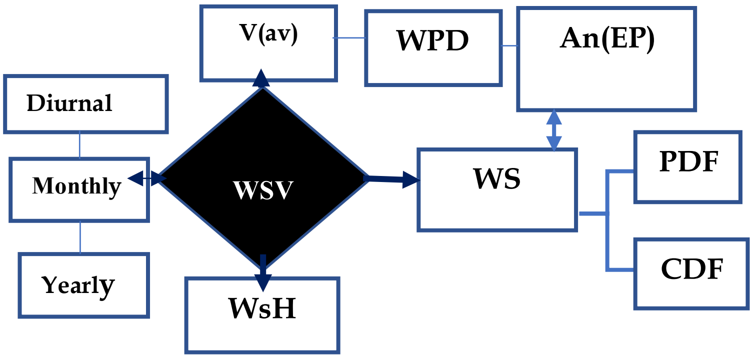


Figure 4.Conceptual frame work developed [42]

The cumulative density function (CDF) in Eq.(2) is informative to know the operating time of the turbine, i.e., how many hours the wind turbine has been outside the power generation limits, which means the probability the speed of the wind (v) is outside or equal to the cut-in and cut-off limits. And also, the proportion of the time the wind speed is within an operational (productive) speed range [38,41].

$$F(v) = 1 - exp\left[-\left(\frac{v}{c}\right)^{k}\right]; (k > 0, v > 0, c > 0) \quad (2)$$

The shape, scale parameters can be estimated by several methods [34, 39, 43]. This study used Least-square fit method to observe distribution as it is explained after: The double logarithm of Eq.(2) yields:

$$\ln\{-\ln[1 - F(v)]\} = k\ln(v) - k\ln(c) \qquad (3)$$

A plot of $\ln\{-\ln[1 - F(v)]\}$ vs $\ln(v)$ gives in a linear line. The slop of the line gives the function, and this $\ln\{-\ln[1 - F(v)]\}$ yeilds $k\ln(c)$. Hence, the shape factor k and the scale factor c are determined. The most occurring wind-speed, v_{mp} $({}^{m}/_{s})$, the maximum energy carrying speed, v_{maxE} $({}^{m}/_{s})$, are calculated based on Eq.(4)&(5) [34, 39].

$$v_{mp} = c\left(1 - \frac{1}{k}\right)^{1/k} \qquad (4)$$

$$v_{maxE} = c\left(1 + \frac{2}{k}\right)^{1/k} \qquad (5)$$

The wind power available per unit area A (m^2) with a speed (v) is given by the (Eq 6-Eq.8) [35, 44-51].

$$p(v) = \frac{1}{2}\rho v^3 \qquad (6)$$

Where; ρ is the air density at the site (kg/m^3). Also the power density of the wind, for a probability distribution $f(v)$, can be determined by eq.7:

$$WPD = \int_{0}^{\infty} p(v)f(v)dv = \frac{1}{2} * \rho * c^3 * \Gamma\left(\frac{k+3}{k}\right) \quad (7)$$

Where Γ is Gamma function and it is the available energy density i.e., energy per month or year E_{an} (Wh) can be given by:

$$WED = \frac{T}{2} * \rho * \int_{vi}^{vf} v^3 * f(v) * dv =$$

$$= \frac{1}{2} * \rho * c^3 * \Gamma\left(\frac{k+3}{k}\right) * T \qquad (8)$$

Where; vi & vf are the starting and the stopping(furling) wind speeds, T is the total hours per year, and $f(v)$ is the Weibull function tailored for the particular wind site. When calculating the energy on an annual basis, T was considered as 8,760h in this study.

2.4. Pumped hydro-storage potential determination

In surveying the potential sites for the upper reservoirs, Google Earth, is used in 3-D mode and the overall determination of the potential followed the procedure sown in Figure 5. The theoretical power of the system can be calculated using Eq.(9) [52, 53].

$$p_c = \rho * g * Q * h * \eta_T \qquad (9)$$

Where: Pc = Power Capacity in Watts, h = head in m, Q = flow rate in m^3 /s, ηT is the efficiency of the turbine and g = is acceleration due to gravity equals to 9.8m/s^2.
Reversible pumps were considered as turbines with an overall efficiency of 70% in the investigation. It is the most used because its installation, maintenance, and operation are cost-effective [54] .

2.4. Solar Energy potential determination

Scientifically, the data required to determine the potential of solar energy in a prospective location is to take measurement of the irradiance for many years. Unfortunately, in Ethiopia, there is no such data, what is available is average sunshine-hour data collected for some years by NMA [29, 31]. In this study Software PVGIS [55] data is used spanning from 2001-2019 to decide on the potential of the three islands. The data is cross-checked against the radiation data calculated from the sunshine hour data. And Angstrom-Prescott model is used to find the equivalent radiation.

3. Result and Discussion

3.1. Wind energy potential of the islands

This section provides a detailed wind data analysis, begins with data obtained from NASA,1978-2018 (Figure 6). As mentioned in previous section, there is a measurement data, 2017-2018, at height of 10m,50m&70m above the ground. That at the height of 50m is compared against data from NASA. The shape-factor (k), and the scale-factor (c) are calculated by Least-square curve fitting method Eq. (3),and MATLAB (version-2018-a).

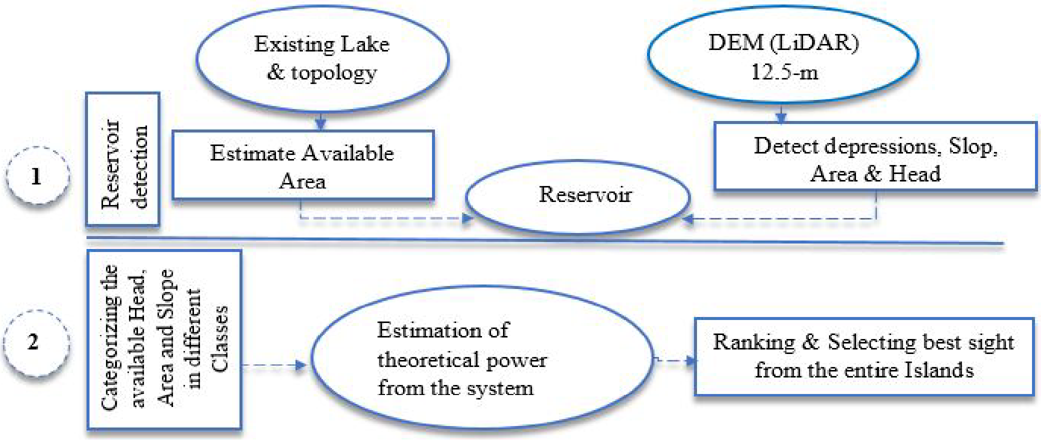


Figure 5. Methodological flowchart for assessing the PHS of the islands.

The Vmp, VmaxE, p(v), WPD, & WED are estimated by using Eq. (4)- (8).

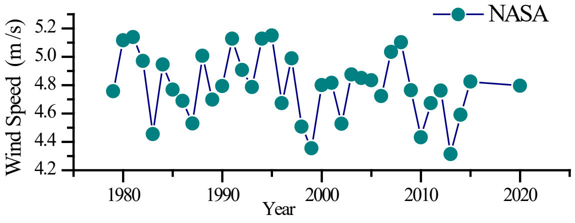


Figure 6. Time series of monthly wind speeds for the study area:(NASA)

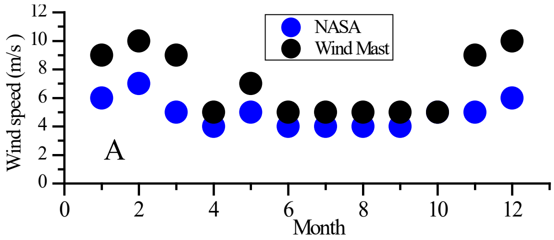


Figure 7.(a) Comparison of measured and data from NASA

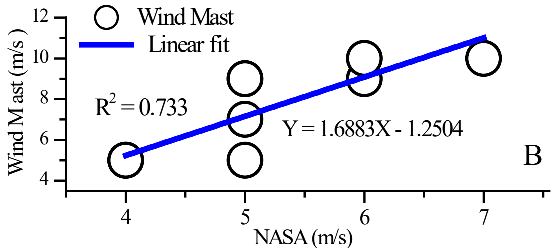


Figure 7. (b) measured VS data from NASA

The comparison of the result is shown in Fig.7(a), and Fig.7(b). The correlation, $R^2 = 0.73$, which can be taken as a good correlation. The authors believe the results achieved here should be good enough to the next level of the research work of hybrid energy supply system design and thereafter to the realization of the results as a project. Based on the literature reviewed, at least a one-year wind speed field data is necessary for accurate resource assessment [56-58]. Fig.8 depicts the wind speed variation over the measurement period. The variation of the wind speeds at 70 m height is 5-10 m/s, corresponding to months of June, July, and August, for the minimum, and December and January for the maximum.

At a height of 50m, the wind speed averages to 7m / s. This, together with the average power density, provides enough information to classify the wind regime as class 4 according to the international wind power classification. Renewable energy scientists recommend class 3 or higher wind power for an economical and profitable wind turbine in a particular area [59].

Knowledge of the wind speed and the wind that carries the highest energy gives confidence for the designer to decide if a wind farm at a site can be developed [39]. Fig.9 portrays the monthly variation of Vmp, and VmaxE through the months of a year, January (1) to December (12).

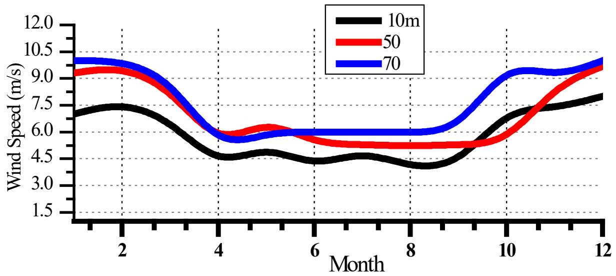


Figure 8.Monthly variation of averaged wind speed at research area (Field data, 2018)

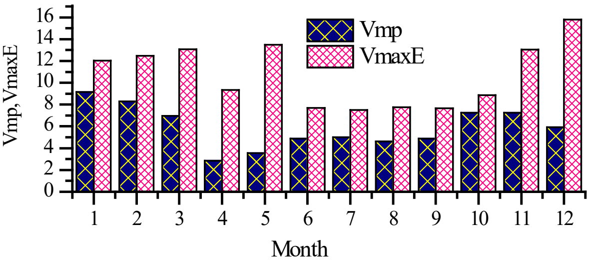


Figure 9.Monthly variation of Vmp & VmaxE

The variation of Vmp & VmaxE are 2.85 - 9.14 m/s & 7.49-13.06 m/s respectively. The Scale factor, the shape factor, the available energy and the power density are provided in Fig.10(a&b) based on Eq.3,7&8.

The wind in the sites is highly variable and gusty for smaller values of k (1.5). moderate for k = 2, and steady for k ≥ 3 [60]. While parameter c is close to the monthly mean wind speed, the range varies between 5.91 to 10.31 m/s, with the lowest in August and the highest in January. The annual mean value of c is 7.8 m/s. The power density varies between 144 - 997 W/m ^{2} from July to December. The minimum wind energy density is 107 kWh/ m^2 recorded in July, and the highest, 741.8 kWh/ m ^{2}.

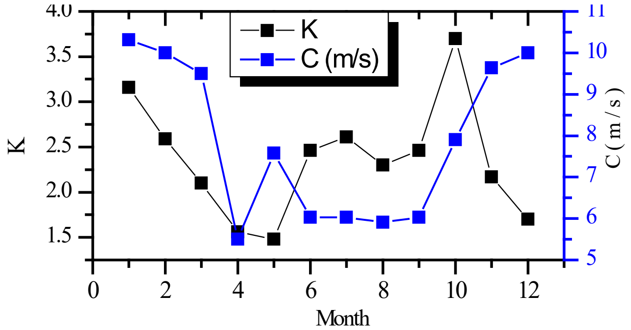


Figure 10 (a).Scale factor and the shape factor, the power density & energy density of the study area.

From Eq.(2) where $F(0) = 0$ and $F(\infty) = 1$, it is possible to calculate the Weibull distribution of the wind. For example, how many hours a typical 70m height wind turbine of 2.5 m/s starting, 16 m/s furling wind speed, and shape factor, k, of 2.36 can stop in a year is calculated as:

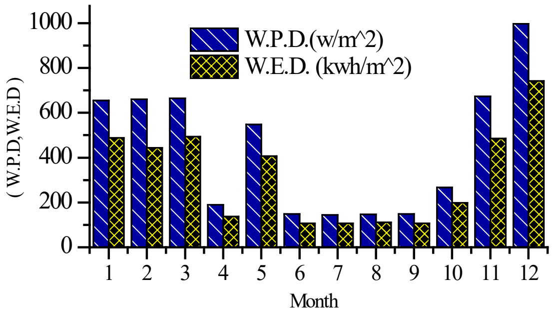


Figure 10 (b). The power density & energy density of the study area.

$$p(0 \le u \le 2.5) = exp\left[-\left(\frac{0}{7.87}\right)^{2.36}\right] - exp\left[-\left(\frac{2.5}{7.87}\right)^{2.36}\right] = 0.064$$

$$p(16 \le u \le \infty) = exp\left[-\left(\frac{16}{7.87}\right)^{2.36}\right] - exp\left[-\left(\frac{\infty}{7.87}\right)^{2.36}\right] = 4.815 * 10^{-03}$$

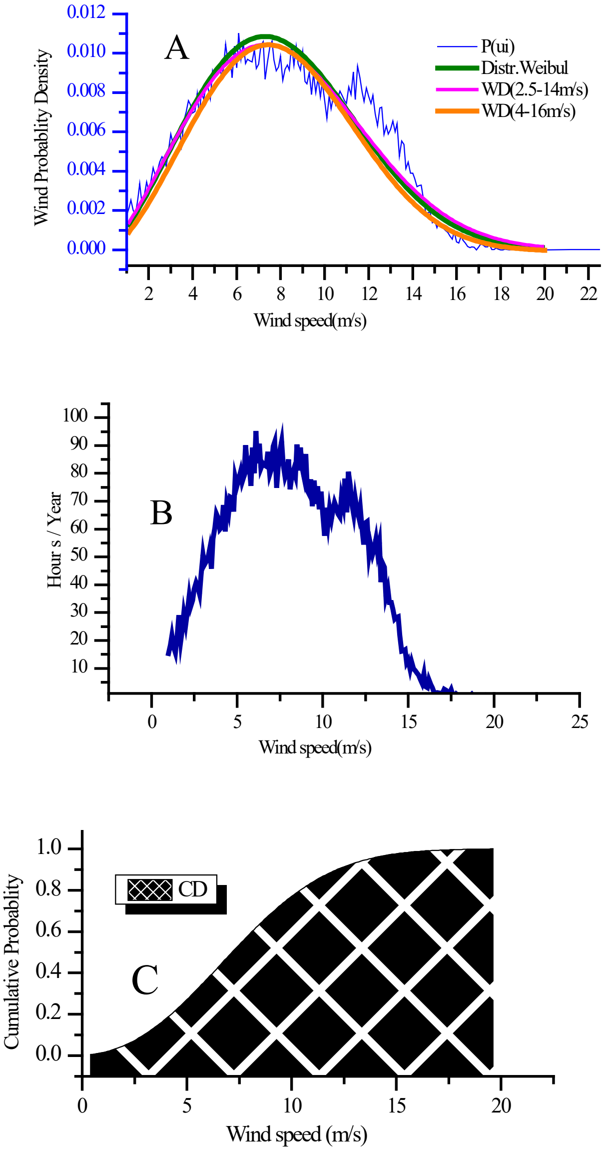


Figure 11.a), b), c) Wind resource, cumulative distribution, and Probability Density function

The wind resource distribution of the island for various types of wind turbines and wind distribution (WD) with an operating range of (2.5-14,4-16 m/s) with its corresponding CDF and the percentage of hours the wind speed at a particular value is presented in Figure 11 (a, b and c). Such analysis is critical to select the appropriate types of the power curve and designing small-scale wind turbines for the region in the future [59].

3.2. Pumped Hydro-Storage (PHS) potential

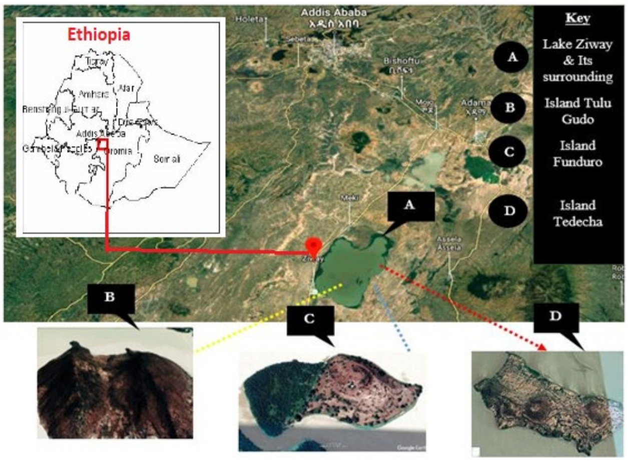


Figure 12. Areal Map of the project area (source: Google Earth 2021)

By using DEM(LiDAR) 12.5-m, and selection metrics: topography, capacity, available area to build upper reservoir, elevation difference, community proximity and relatively lower slope the potential is determined. Fig.12 shows the aerial view and the geographical layout of the lake and its three islands, Tulogudo, Funduro, and Tsedecha.

3.2.1. Determination of Head

The available head for the islands is determined using the digital elevation model LiDAR at 12.5-m spatial resolution and is presented in 3D DEM output in a 3D view as shown in Figure 13. In a previous study, possible topologies for the analysis of PHS were identified [24] by converting an existing water body into a pumped storage system through investigation of a second (upper) reservoir, which can be a natural dispersion or artificially created one.

This study considers a number of selections metrics that include high elevation, relatively lower slop, enough area for the upper reservoir, and proximity to the community. The extracted head is in the range of 50-300 m, 50-200 m, and 50-100m for Tulugudo, Tedecha, and Funduro, respectively.

The power generation capacity of the PHS depends on the head available Eq.(9). Hence, according to the search criteria, Tulugudo Island turned out to be of the highest head, but also with a relatively higher slope. Tedecha has a relatively lower head, but also with a relatively lower inclination. Through observation of the results the authors decided Tedecha to be the best potential candidate for PHS and Tulugudo as a second best.

The third potential candidate is Funduro. The decision is made based on the study results previously reported [25]. When the slope of the natural ground surface is mild (e.g., slope 10%), a slope value of 0-10 was chosen as an appropriate flatness of the topography and thus it's a plus for PHS site selection [61].

The reclassifying tool is used to filter out areas with slopes between 0 and 30 before transforming them into polygon areas. These polygon areas are now potential reservoir sites, as presented in Figure 14.

Within a head range of 50-100m the reservoir has a capacity of 51100m^3. With a 60m head and assuming 0.0833c discharge hours and 70% generation efficiency, the flow rate of discharge is 1.208 m^3/s, the power generated is 498 KW this can be small-scale PHS with a minimum storage capacity of 5976 KWh. Finally, based on what is explained above for the selection the PHS of the islands is determined and is presented in Figure 15.

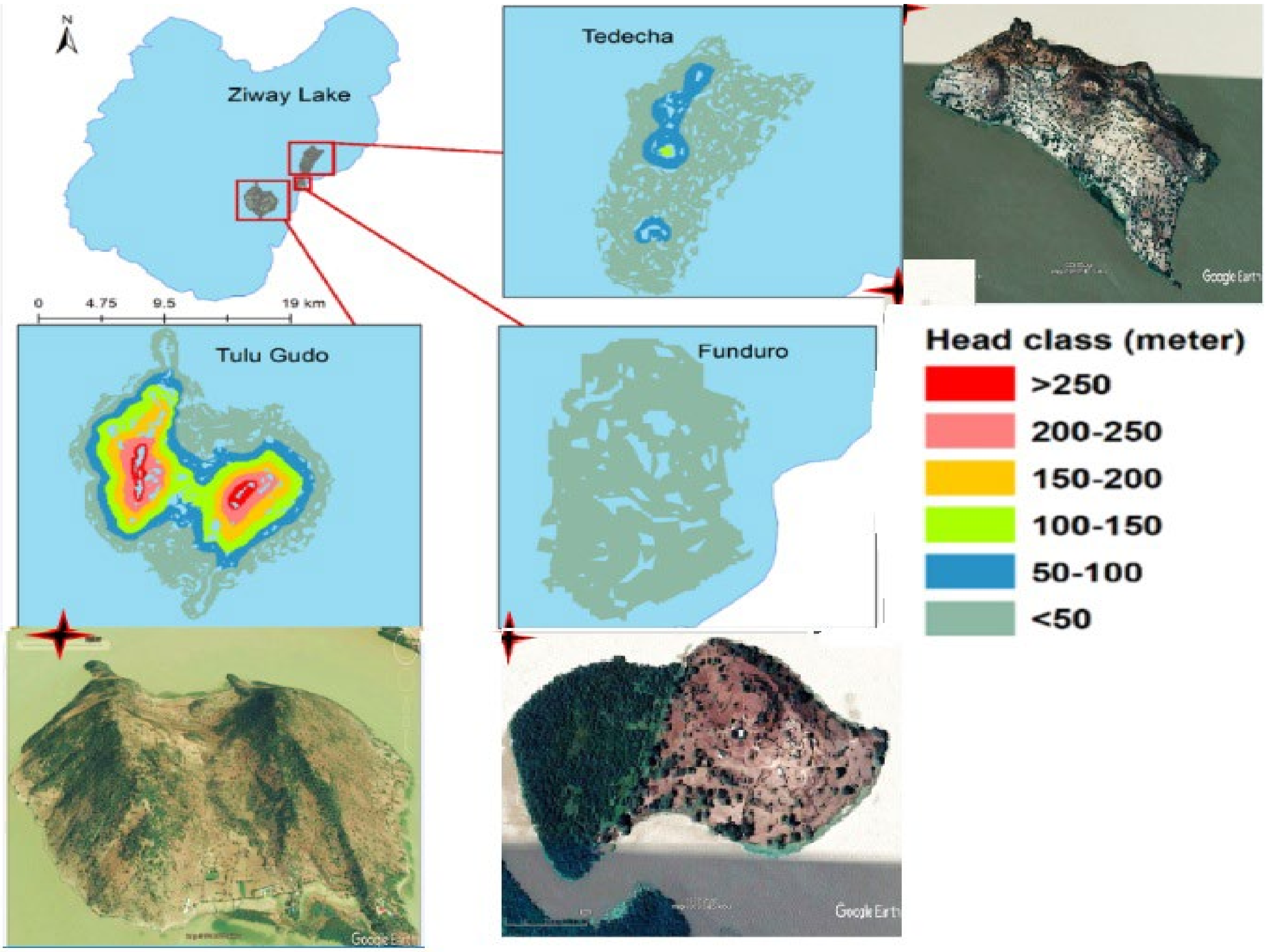


Figure 13.Available heads (DEM, Google Earth, 2021)

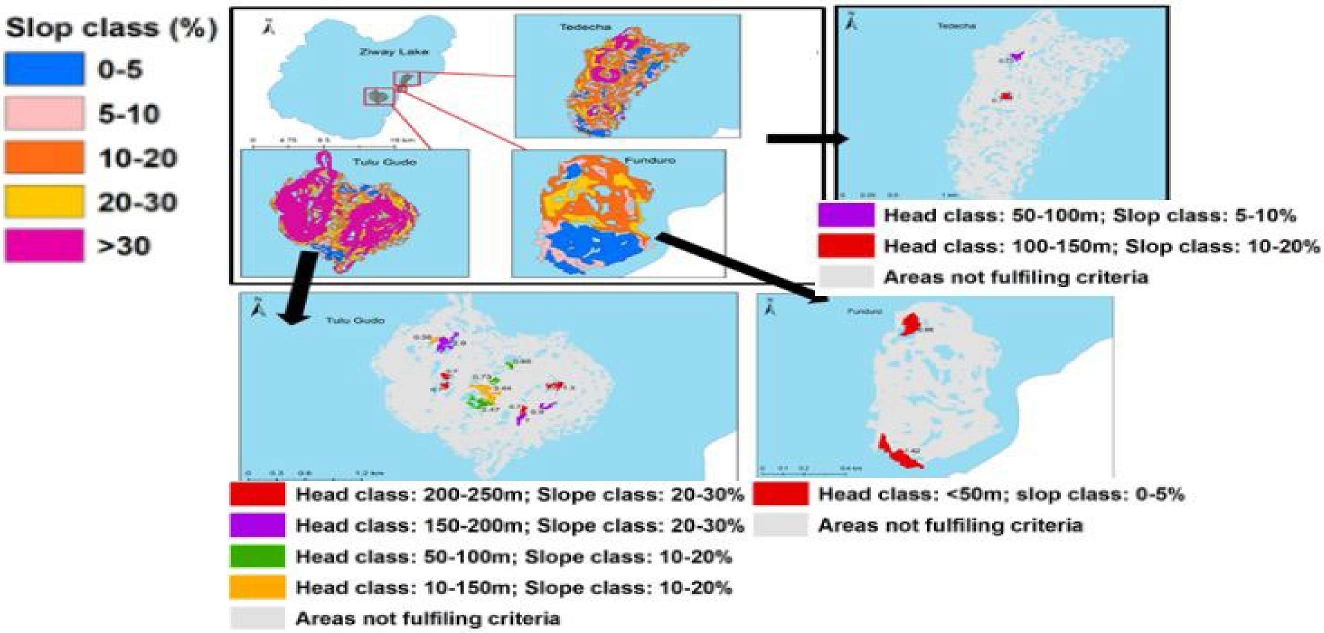


Figure 14. Slop class, area, and corresponding head according to (LiDAR, DEM,2021)

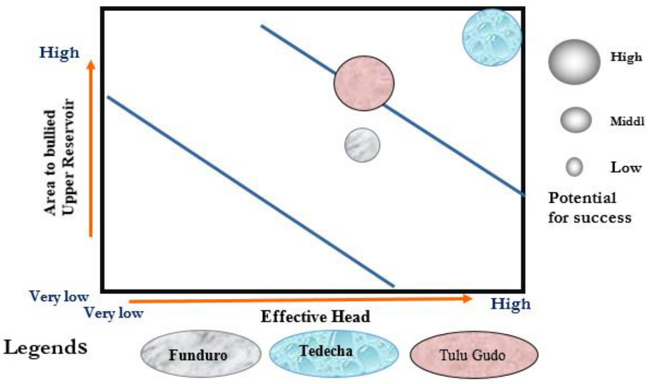


Figure 15. Pumped hydro-storage potential of the islands

3.3. The solar energy potential

This section discusses the solar energy potential of the Islands. Photovoltaic Geographical Information System (PV-GIS) irradiance data is retrieved for the three of the islands. Annual irradiation deficit due to shadowing on horizontal plane was evaluated independently. Averaged irradiance is found to be 6.1 kWh/m^2 /day; whereas 6.3 kWh/m^2 /day is what is registered by the Angstrom-Prescott model. By following the principles of solar energy system designs the authors used PV-GIS irradiance data (the lower) to investigate the potential of the islands and is presented in Fig.16.

Lower level of radiation is observed in July & August, which is absolutely true, as this is the rainy season in the country and is mostly cloudy. For the rest of the year, it is of a relatively higher level of radiation as it is shown in the Fig.16.

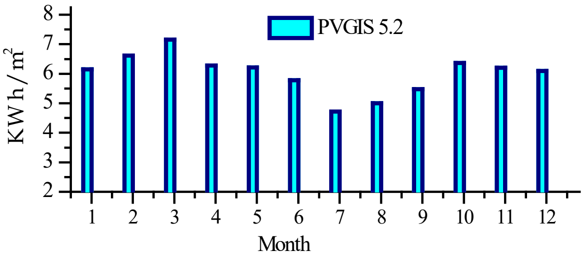


Figure 16.Monthly irradiation

3.3.1. Determination of the Optimal PV panel Inclination

Experimenting on the amount of radiation at different module tilt angles facing south would help to find the optimal angle to absorb high solar energy, even though usually it is customary to use the latitude angle of the location. The experimental result is shown in Fig.17. The letter H is the irradiance and the numbers in the brackets following H show the inclination degrees.

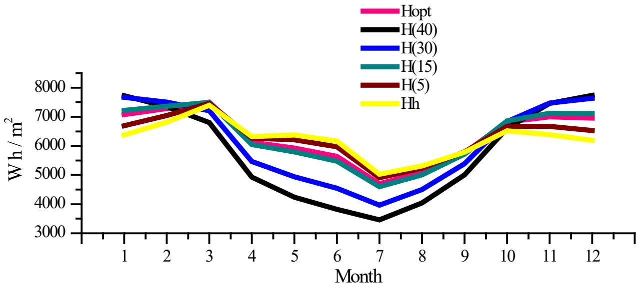


Figure 17.Daily solar radiation for differently tilted surface.

Figure 17 shows that increasing the angle of inclination of the (PV) modules results in higher levels of irradiation during the dry seasons (when the sun is in the south) and decreasing the angles results in lower levels during the rainy months (when the sun is in the north). The daily average global radiation in a year varies depending on the slop of the (PV) modules, ranging from 5.610 kWh/m^2 /day to 6 kWh/m^2 /day, with a maximum of 6100Wh/m^2 /day at 12°(Hopt). The annual irradiation deficit due to shadowing is estimated to be close to 0%. For a fixed angel annually, the system can deliver an average of 135 kWh, maximum in march and minimum in July & August. Eventually the study will proceed the next step of this paper based on the graphical abstract presented on Figure 18.

Figure 18. Proposed Eco-friendly electricity supply system of the Islands:(Google Earth, 2021)

4. Conclusions

There are numerous initiatives to increase access to electricity, but its practicality rate is well below what the UN-Energy goal 7 set for 2030 [1]. This is even worse in Sub-Saharan Africa, and hence true in Ethiopia too. The contribution of this paper would be essential to the achievement of SDG 7. In this study, the authors analysed the sustainable energy technology options of renewables: wind, PHS, and solar energy, as a first step before designing a low carbon energy supply system planned in the next step. This study used different methodologies in line with the objectives of the study including experimental work for obtaining a reliable and plausible data. In addition to the experimental work it also cross-checked the data rigorously against the previous studies and international data sources [29-31, 33, 62] to evaluate the degree of variations. Regarding the wind energy potential, the experimental research results showed a correlation of 0.73% to the data obtained from NASA database. The annual average wind speed at 50m and 70 m is 7 m/s & 7.63 m/s respectively and WED for the 70 m height is 318.8 kWh/m ^{2}. The scale factor c is 7.8m/s at 70m with a corresponding shape factor, k, 2.3. Based on such results and the reviewed literature, conclusion is that the wind power in the region falls within the category of class- 4, which implies that windfarm in the region is economically feasible [59]. It is to be noted that renewable energy professionals usually recommend international wind power class-3 or above [59] for viable implementation of wind power. Also, this study considers PHS as part of the planned hybrid energy system design, which previously may not have been given a serious attention for a continuous energy supply system. The potential of the PHS is determined by GIS-based topographic analysis using digital elevation models (DEM). The elevation information of the study area is extracted from DEM LiDAR data at 12.5-m spatial resolution. In visualizing potential sites for upper reservoirs, Google Earth is used in 3-D mode. Accordingly, twelve upper reservoirs were identified within the head rang of 50-250, 50-200, and 50-100m. Island Tedecha is found to be the best candidate followed by Tulu Guddo & Funduro. The investigation proved that small-scale PHS can be developed with a minimum storage capacity of 5976 KWh. Finally, the study investigated the solar energy potential of the study area. Accordingly, the average irradiance level annually is found to be 6.1 kWh/m ^{2} /day at an optimum tilt angel and the annual irradiation deficit due to shadowing is found to be close to 0%. This all helped us to conclude the Island as a potential area to generate low carbon energy supply system. The result of this paper would be a great input for our next work of designing the low carbon energy system from renewables Figure 18. The findings here are applicable to many developing countries with electricity supply shortages.

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