A sustainable energy mix for small islands in the Pacific Oceans. The case study of Vanuatu

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***Abstract*—The installation of technologies supplied by Renewable Energy Sources is mandatory to improve the environmental sustainability and loosen the dependence on fossil fuels. Furthermore, the energy transition can strengthen the stability of the energy market, especially in small islands. At the same time, the need for large infrastructure construction could be alleviated in developing areas. In this context, the proposed paper analyzes the current scenario of the small developing countries of the Pacific Ocean. In particular, the case study of Vanuatu is assessed, analyzing the available renewable energy sources: solar, wind and sea wave.**

Keywords—Pacific Oceans, small island, SIDS, Vanuatu, Energy Mix, sea wave

I. INTRODUCTION

In every part of the world, plants supplied by renewable energies are spreading. Advantages and disadvantages are well known in literature. The main advantage is the possibility to produce electrical energy in a more environmentally friendly way, without the use of fossil fuels. Renewable energies are well diffused worldwide, thence the adoption of these sources reduce the dependence from a limited number of countries [1], [2]. On the other hand, the main disadvantages are the low energy density and the aleatory of the energy production from some of them (especially solar and wind) [3], [4], [5].

However, the carbon neutral emission of the energy sector is a shared worldwide target in order to limit the global warming. For this reason, great efforts are being made to improve the performance of these technologies and allow a proper management of the electrical grid [6], [7]. The utilization of renewable energy sources is an important opportunity also for small islands and remote areas. Indeed, as introduced above, fossil fuels are concentrated in limited areas in the worlds. Thus, long trips are required to refill the fuel tanks in case of remote regions. On the contrary, renewable energy sources can be found in all territories. Of course, in each area a limited span of renewable energies could be more suitable [8], [9]. Small islands and remote areas are usually supplied through underdeveloped and fragile electrical grids, using diesel engines as prevalent energy source. Small standalone DC grids are sometimes also adopted in rural areas [10], [11], adding photovoltaic panels, small wind turbines [12], and batteries [13], [14]. In this context, the United Nation in 1994 identified a list of small and isolated countries with the acronym SIDS (Small Islands Developing States), that are more exposed to the fluctuation of prices of raw materials and fossil fuels. The SIDS group includes 58 states, among which Caribbean (29 countries), Pacific (20) and AIMS (acronym of Africa, Indian Ocean, Mediterranean and South China Sea, 9 countries) [15], [16].

TABLE I. RES USED IN THE SMALL COUNTRIES OF THE PACIFIC OCEAN

Country	Surface [km^2]	Pop.	% RES Elect.	Share in RES generation: Solar	Hydro	Wind	Bio	Geo
Cook Islands	237	15,040	34.2%	100.0%	0.0%	0.0%	0.0%	0.0%
Fiji	18,274	896,444	59.7%	1.9%	82.3%	0.1%	15.8%	0.0%
French Polinesia	3,521	278,786	30.4%	20.7%	79.3%	0.0%	0.0%	0.0%
Kiribati	811	119,940	13.9%	100.0%	0.0%	0.0%	0.0%	0.0%
Marshall Islands	181	61,988	2.5%	100.0%	0.0%	0.0%	0.0%	0.0%
Micronesia	702	104,468	6.3%	75.0%	25.0%	0.0%	0.0%	0.0%
Nauru	21	12,623	7.5%	100.0%	0.0%	0.0%	0.0%	0.0%
New Caledonia	18,275	238,000	15.6%	29.8%	60.5%	9.7%	0.0%	0.0%
Niue	261	1,937	13.3%	100.0%	0.0%	0.0%	0.0%	0.0%
Palau	459	18,024	2.4%	100.0%	0.0%	0.0%	0.0%	0.0%
Papua New Guinea	462,840	11,781,559	60.4%	0.3%	65.0%	0.0%	3.0%	31.7%
Samoa	2,831	205,557	37.8%	36.9%	63.1%	0.0%	0.0%	0.0%
Solomon Islands	28,896	7,007,851	6.7%	42.9%	0.0%	0.0%	57.1%	0.0%
Tonga	748	100,209	13.5%	70.0%	0.0%	30.0%	0.0%	0.0%
Tuvalu	26	11,900	16.0%	100.0%	0.0%	0.0%	0.0%	0.0%
Vanuatu	12,189	307,815	28.2%	31.8%	36.4%	27.3%	4.5%	0.0%

In the Pacific Ocean, there are many islanded countries, forming the Oceania. This region covers a surface of 8,525,900 square kilometers and is home for 44.4 million of inhabitants. The welfare is quite variegated. Among the developed countries, it is possible to cite Australia, French Polynesia, Hawaii, New Caledonia and New Zealand. On the other side, there are many developing countries. Some statistics are listed in Table I [17].

Focusing on the energy sector, Table I reveals a marginal contribution from renewable energy sources, lower than 35%. The only relevant exceptions are Fiji (hydropower and biomass cover 59.7% of the energy demand) and Papua New Guinea (hydropower and geotherm satisfy the 60.4% of the energy demand). Solar energy is commonly used in all countries, although this source plays a marginal role [18], [19].

Hydropower is used in some countries, among which: Fiji, French Polynesia, Micronesia, New Caledonia, Papua New Guinea, Samoa, and Vanuatu.

Wind energy production occur in Tonga, Vanuatu, and New Caledonia. Biomass is used in Solomon Islands, Fiji, Vanuatu, and Papua New Guinea.

Finally, geothermal energy is used only in Papua New Guinea.

II. The Case Study: Vanuatu

The Republic of Vanuatu is a small independent country, placed in the middle of the Pacific Oceans. Indeed, this archipelago is approximately 1750 km east of northern Australia, at almost the same longitude of New Zealand. There are many other small-islanded countries in this region, the closer are: New Caledonia (540 km), Solomon Islands (640 km) and Fiji (840 km).

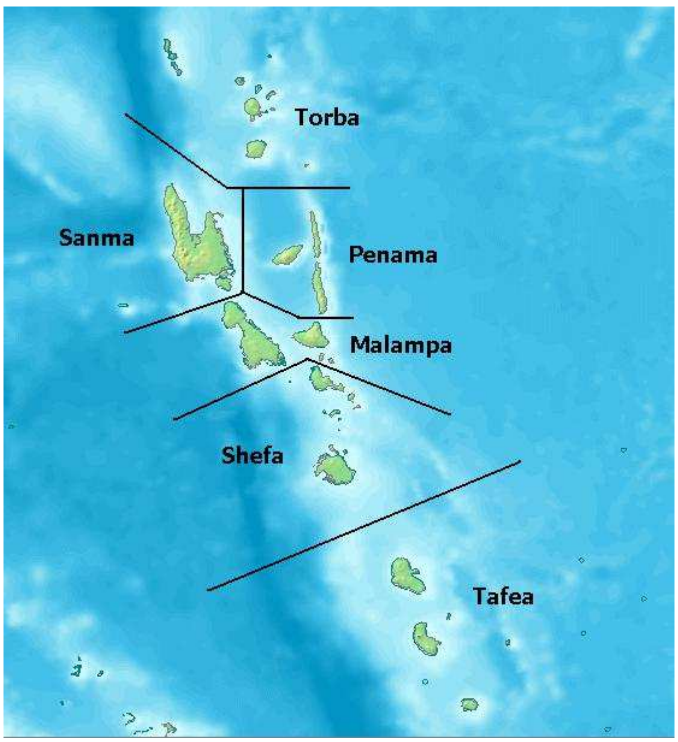

Fig. 1. Map of Vanuatu, reporting the provinces

The archipelago is composed of 83 islands, of which 65 are inhabited. Only 14 of them have an extension over 100 km^2. The total extension (including the territorial sea) is about 12,280 km^2. The major islands are listed in Table II, reporting the surface, highest point and the population based on 2020 Census [20]. Vanuatu is home to almost 300,000 citizens, of which 66730 live in urban areas, i.e. Port Villa in Efate and Luganville in Espiritu Santo, whereas a major part of population lives in small villages and rural areas (77.75 %). The population is currently increasing with an annual rate equal to 2.3%.

TABLE II. Population and Size of the Major Islands of Vanuatu

Name	Surface (km^2)	Highest elevation (m)	Population
Espiritu Santo	3955.5	1879	38360
Malekula	2041.0	879	32294
Efate	899.5	647	43159
Erromango	891.9	886	18759
Ambrym	677.7	1334	8528
Tanna	550.0	1084	40603
Pentecost Island	490.0	947	21097
Epi	444.0	833	8023
Ambae	398.0	1496	9856
Gaua	330.0	767	3467
Vanua Lava	314.0	921	3270
Maewo	269.0	795	4654
Malo	180.0	326	4804
Aneityum	159.2	852	1513

As many other small countries in the Pacific Oceans, Vanuatu has a volcanic origin: Lopevi and Mount Yasur are two active volcanoes, but underwater volcanoes are also present. Consequently, earthquakes and eruptions occasionally occur.

Most of the islands are steep, with unstable soils and little permanent fresh water. The shoreline is mostly rocky with fringing reefs and no continental shelf, dropping rapidly into the ocean depths.

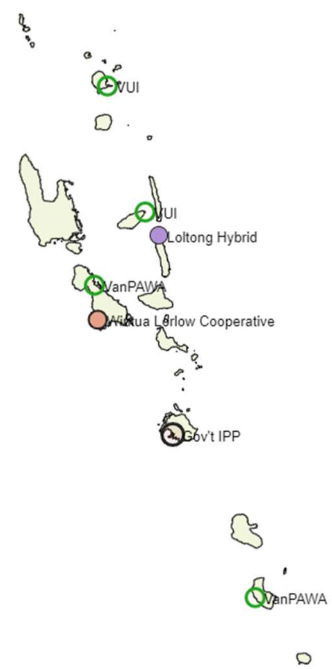

Fig. 2. Map of Vanuatu, reporting the energy utilities [21]

Focusing on the energy sector, the several small islands of Vanuatu are equipped with limited standalone grids. Despite the progressive electrification of the islands, still today a relevant part of the population does not have access to the electricity (32.67 % in 2020, about 87% in 1995) [22]. The target is to guarantee the electricity to all citizen by 2030.

As many other small island countries, in Vanuatu the electricity production is mainly entrusted to diesel engines, as shown in Fig. 3.

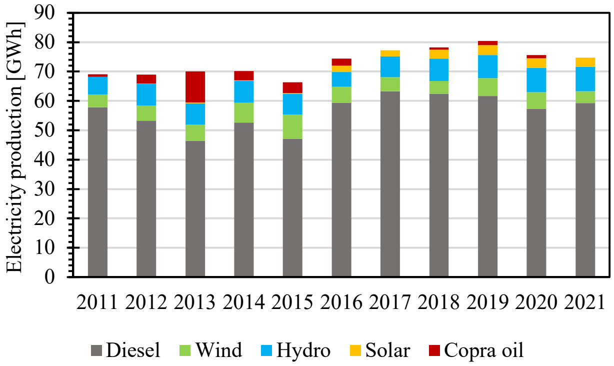

Fig. 3. Electricity production by sources in Vanuatu

Copra oil (extracted from coconut) is blended with diesel, in order to limit the importation of fossil fuels. Wind energy is currently produced only in Efate, close to Port Villa. The rated power is 3.4 MW, able to produce about 4.13 GWh/h in 2021.

A hydropower plant is located in Espiritu Santo, close to Luganville. The rated power is 1.2 MW, able to produce 8.28 GWh in 2021. Photovoltaic panels are also installed, mainly in Port Villa (2.45 MW). Small plants are diffused also in the other small islands (0.25 MW).

Thus, summing all the energy sources, in 2021 the electricity production was essentially based on diesel engines (59.21 GWh, 79.26% of the energy demand). The remaining part of the electricity demand was covered by hydropower (8.28 GWh, 11.08 %), wind (4.13 GWh, 5.53%) and photovoltaic panels (3.08 GWh, 3.08 %).

Since the population is increasing, it is expected that the energy demand could growth as well, achieving the values 140-160 GWh/y by 2030.

In order to improve the sustainability of the energy sector, in the following paper the authors assess the availability of renewable energy sources.

III. Energy scenarios

In order to improve the energy sustainability of the energy sector, three renewable energy sources are investigated.

A. Solar energy

The solar radiation was analyzed by using the GIS-tool global solar atlas. As shown in Fig. 4, the radiation is almost stable during the entire year and limited variations can be found in the different islands.

The evaluation considered the installation of tilted panels oriented to North (all islands are in the southern hemisphere), with a tilted angle between 14° and 18°.

The authors propone the installation PV panels, assuming the ratio of 100 W per person.

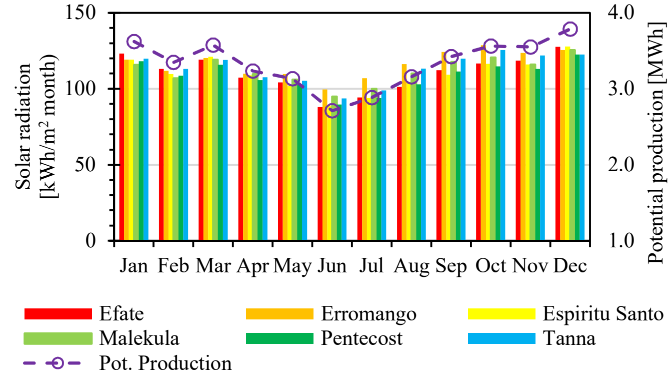

Fig. 4. Solar radiation in Vanuatu and potential production of PV panels

Thus, considering the current population, a total installation of 30 MW of PV plants is required, while only 2.7 MW are currently used. In this scenario, about 40 GWh could be produced by solar radiation, covering almost half of the current energy demand.

B. Wave energy

In 2015 the WACOP project assesses the wave climate in the Pacific Ocean. These data are precious to understand the wave energy potential and the erosion of the coastline [23], [24]. About Vanuatu, three reference points were considered: Efate, Luganville and Port Villa. The following Fig.s 5, 6 and 7 report the trend of the monthly average values of wave height, wave period and wave direction in these reference points [25], [26], [27].

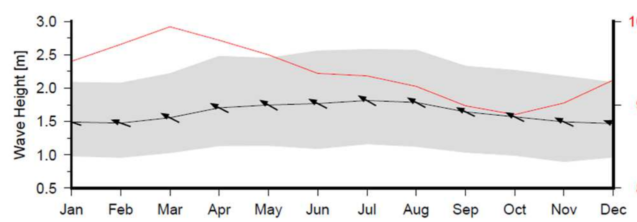

Fig. 5. Trend of wave height, period, and direction in Efate

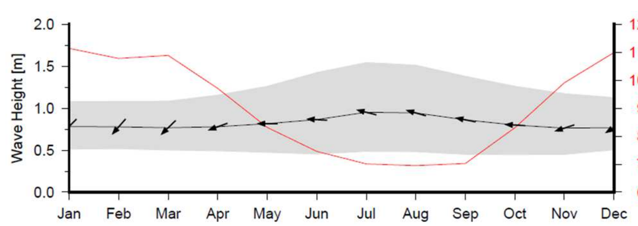

Fig. 6. Trend of wave height, period, and direction in Lugaville

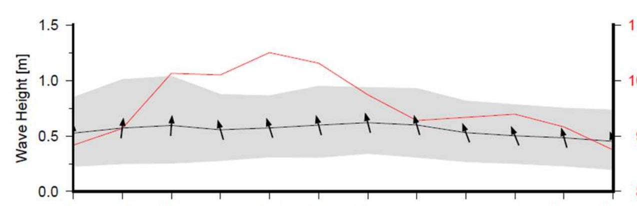

Fig. 7. Trend of wave height, period, and direction in Port Villa

By using these data, the wave energy flux was evaluated from the following relation:

$$\psi(H_s, T_e) = \frac{\rho g^2}{64\pi} H_s^2 T_e$$

Where ρ is the water density (1025 kg/m^3), g the gravity acceleration, H_s is the significant wave height and T_e the wave energy period. Fig. 8 shows the annual trend of the wave energy flux. It is interesting to observe that the site of Efate has a greatest energy potential, thus a wave energy farm could be installed in this area. The waves come quite steadily from east southeast.

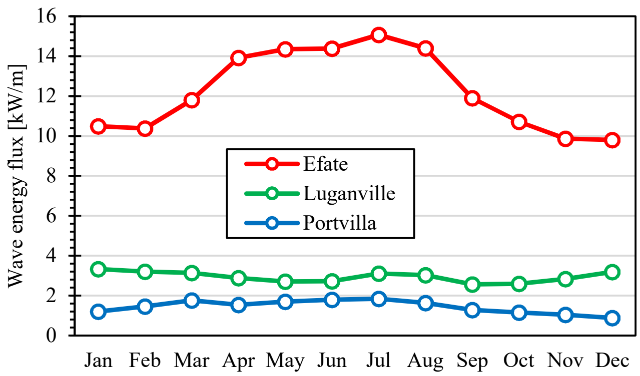

Fig. 8. Trend of wave energy flux

For the wave energy harvesting, in literature some potential technologies are proposed [28], [29]. In particular, the authors considered a wave energy converter assessed in previous studies [30].

This machine is designed for an offshore installation. It is essentially composed by two floating buoys, designed to create an alternative linear motion among the parts. A mechanical motion converter is installed inside in order to run an alternator and produce electrical energy.

Considering the wave climate in Efate, each WEC interacting with 8 m of wavefront is able to produce electrical energy according to the trend reported in Fig. 9. Thus, assuming the realization of a wave farm composed by 10, an annual production of 3 GWh was estimated.

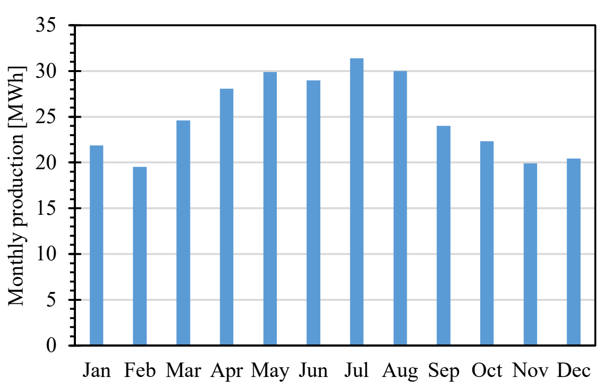

Fig. 9. Annual producibility from a single Wave Energy Converter

C. Wind energy

The evaluation of wind energy potential was based on data extracted from the Global Wind Atlas [31]. A map of the average wind speed at 50 m above sea level is reported in Fig. 10.

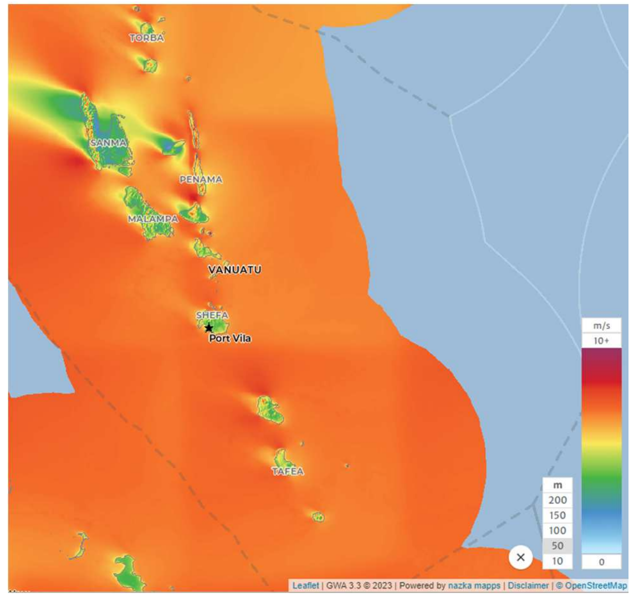

Fig. 10. Average wind speed at 50 m above sea level in Vanuatu

For each major islands the GIS file on wind climate was extracted from the Global Wind Atlas.

The authors selected a 60 kW wind turbine [32], [33], in order to limit the visual impact. This area is exposed to extreme weather condition. The current energy demand is also limited, as well as the development of the existing electrical grid. For all these reasons, a greater size of wind turbines may be inadvisable. The power output of the selected wind turbine as function of wind speed is reported in Fig. 11.

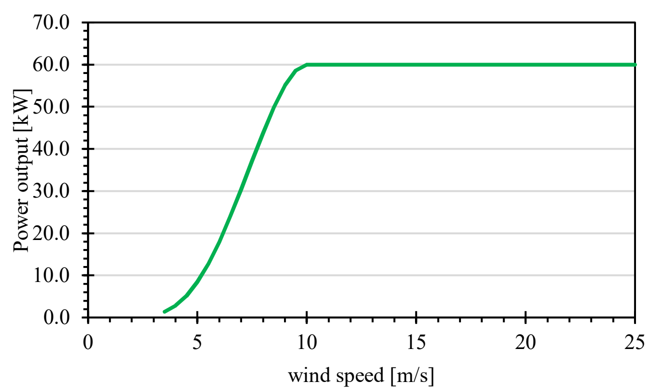

Fig. 11. Power output function of speed for the selected wind turbine

For the main islands, the specific producibility from a single wind turbine was evaluated, considering the proposed wind turbine and the data on wind speed. The number of proposed wind turbine was also evaluated, according to the data on the energy demand. The results are reported in Table I.

TABLE III. PRODUCIBILITY FROM WIND ENERGY

Island	Lat. [°]	Long. [°]	Prod. Min. [MWh/y]	Prod. Max [MWh/y]	n. turbines
Vanua Lava	-13.866	167.528	186.6	268.9	1
Espiritu Santo	-15.466	167.229	179.4	187.2	19
Malekula	-16.501	167.783	220.3	294.5	16
Efate	-17.697	168.223	199.5	276.9	21
Tanna	-19.594	169.423	265.7	340.1	20
Erromango	-18.847	169.123	220.3	300.4	9
Epi	-16.650	168.203	268.9	300.4	4
Ambae	-15.301	167.955	250.9	303.1	4
Ambrym	-16.242	168.070	239.3	283.0	4

Considering the installation of 98 turbines, the expected annual energy production ranges from 21.6 to 27.4 GWh/y.

IV. CONCLUSION

The paper analyzed the energy sector of Vanuatu, an archipelago in the middle of the Pacific Ocean. As many other small countries, the current energy mix reveals a strong dependence from fossil fuel. A marginal contribution is currently given by hydropower, wind, and solar energy.

This condition is unsustainable from an economic and environmental point of view. Thus, the paper assessed the available energy sources, in order to evaluate the potential installation of plants supplied by RES.

The proposed mix suggests the installation of 30 MW of photovoltaic panels. A wave farm, composed by 10 devices (80 kW each), could be installed in Efate, in order to produce about 3 GWh/y.

Wind turbines could be installed in the islands with an higher population density. The proposed solution suggests the installation of 98 wind turbines (58.8 MW in total), in order to produce 24.5 GWh/y. Finally, the existing hydropower plant is maintained.

In this way, the entire energy demand could be covered by renewable energy sources and using the existing diesel engines as an emergency backup.

Future works will assess the effect of this high contribution from renewable energy sources, considering the fragile local network.

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