Renewable Generation Electric System

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ABSTRACT

A stable and sustainable energy industry contributes indubitably to the business development, as well as to guarantee the quality of life of a population. However, the economic and social development of insular regions is very vulnerable, due to the high external energetic dependency. Therefore, it is necessary to change the current paradigm of those regions, to take advantage of their endogenous resources to generate electrical energy. The developed work analyses the potential renewable energies (wind and solar) present on the island of Brava, Cape Verde, and assesses its capacity to combine them with an energy storage system that can meet the energetic requirements of the island. The first step consists in the analysis and profiling of the data (energy consumption, solar radiation, wind speed) observed in the island for one year. Simultaneously, several types of storing technologies are analyzed to find the best fitting solution, given the characteristics of the electrical system of the island. The next step consists in the development of a mathematical model, based on LCOE calculus and on the renewable penetration level that determines the optimal mix of power to install of each technology. The results allow to conclude that, despite the inferior solar power generation when compared to the wind power, the most economical solution to the implementation of a 100% renewable system consists of an electricity production park primarily composed by solar powers.

Keywords: Brava Island Case Study, Optics, Photovoltaic Technology, Photovoltaic System, Solar Energy.

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I. INTRODUCTION

In the modern world, the energy sector is of vital importance to ensure the socio-economic sustainability of every country, given that energy is present in almost every services and products.

The growth on the demand of electrical energy is directly associated with the progressive growth of the countries. The most industrialized countries register the highest consumption per capita (kWh per capita). On the other hand, emerging economies register the highest growth for electrical energy consumption. According to the International Energy Agency (IEA), between 1990 and 2013 the consumption of electrical energy grew at a rate of 3% per year. If this trend continues, it means that the electrical energy consumption will duplicate over the next 24 years. Given these predictions, and if the paradigm of the global electrical production remains unchanged, it means that the higher consumption will lead to a higher usage of fossil fuels, which will increase gas

emission and worsen the greenhouse effect and global warming [1-20]. Besides the environmental damages, the high dependency on the fuels in which the replenishment rate is lower than its consumption will be a big problem. Furthermore, the high dependency on these resources increases the vulnerability of the countries to changes in the fuel price, which is extremely sensitive to small geopolitics changes, and environmental catastrophes. This constraint has a higher impact in the electrical energy production in small and off grid systems, in which islands are a part of. These regions have a high external dependency, given their production parks use mostly oil and by products, which need to be imported most of the times. For example, in 2010 more than 95% of the electrical energy produced in archipelago of Cape Verde had oil and diesel as raw material [2].

The need to satisfy the growth of the consumption of electrical energy in a secure and sustainable way has promoted the development of renewable energy technologies. With the high demand for them, came their mass production

and consequent lowering of the prices, thus allowing these technologies to compete with the conventional ones [1,3,6,7,10]. Therefore, the introduction of renewable energies in off-grid systems became interesting from both environmental and economical point of view [6,7].

In off-grid systems, ensuring the reliability of the electrical energy system (EES) is a difficult and expensive task [6]. The difference between consumption during peak and normal hours, as well as the need to guarantee the security of EES, means that the generators will need to work during extreme conditions. Besides lowering of the efficiency of the generators, it also wears down the equipment, making maintenance operations more frequent. These factors contribute to the cost increase of the electrical energy in these regions, which makes it harder to develop the local economy. For that reason, the renewable energy production is considered a solution to lower production costs. However, the intermittent and stochastic nature of such energies makes it hard to balance the production and consumption. To solve that challenge, the storing systems (SS) have a major role, by storing energy when there is a surplus, and to provide when there is a deficit. Nowadays, there are technologies to store energy under several ways (thermal, chemical, mechanical, etc.), being necessary to analyse each solution to find the best fit [6-20].

As previously mentioned, archipelagos of Cape Verde possess a high dependency on fossil fuels, which are nonexistent in their territory. On the other hand, the potential of renewable resources (solar and wind) is very high [6,7]. The introduction of renewable energy production in the archipelagos will reduce the high dependency on fossil fuels, which would contribute to the balance of international transactions. In the energy plan for Cape Verde, in 2020 it is expected a renewable energy penetration of 50% [2], and one of the projects to achieve that goal is Brava 100% Renewable.

Therefore, the main objective of this work is to evaluate the viability of renewable energies (wind and solar) to satisfy the electrical energy consumption of the island of Brava [6,7].

II. CASE STUDY

The island of Brava is one of 10 islands that constitute the archipelagos of Cape Verde, and it is included in the group of Sotavento islands. With only 67 Km² and around 6000 inhabitants, Brava is the smallest populated island in the archipelagos. To assess the reliability of making the production of electrical energy of the island 100% renewable, a measurement campaign with a duration of 1 year was conducted, where the consumption, radiation, temperature, and wind speed were recorded in 10 minutes intervals. The electrical energy consumption was measured in the only thermal power plant on the island (Favetal). On the other hand, the measurement of the renewable potential was done in the Areas for the Development of Renewable Energies (ADRE), identified on the atlas of renewable energies of the archipelagos of Cape Verde [4]. The ADRE on the island of Brava are located next to the thermal power plant, and close to the most important town of the island.

A. Consumption Profiling

The annual consumption registered during the campaign achieved the value of 2.6 GWh. The domestic sector is responsible for the highest consumption of electrical energy of the island. The distribution of the other sectors is shown in Figure 1.

Fig. 1. Estimated distribution of demand for 2013 [2].

The weight of the domestic sector in the energy consumption is highlighted by the low variation of the daily load diagrams between the weekly days, and by the peak consumption that occurs between 19h00 and 22h00. The electrical energy production system of the island of Brava is composed exclusively by a single thermal power plant, equipped with three synchronous diesel generators with a total installed power of 1320 kVA (1056 kW). The cost of raw materials is responsible by the biggest cost on the production of electrical energy, making the local economy strongly affected by the fluctuations of the diesel price.

Taking into consideration the goals set on the renewable energy plan for Cape Verde for 2020, the consumption extrapolation is done for that year. Therefore, the consumption for 2020 results from the extrapolation of the measured consumption in 2013, considering the mean annual growth (TCMA) of 3.2% [2]. According to expression 1, the consumption for 2020 will be of 3.23 GWh.

$$TCMA = \left(\frac{Load_{2020}}{Load_{2013}} \right)^{\frac{1}{2020-2013}} - 1 \quad (1)$$

If we assume that until 2020 no intervention is done in the thermal power plant, and to fulfil the security requirements of UCTE referring to the biggest fault of the biggest thermal group, the usage factor of the thermal power plant goes up to 116%. This situation indicates that the thermal power plant will not have capacity to ensure the required energy during peak hours.

B. Renewable Resources Profiling

The campaign of wind power measurement shows a high potential for this resource. However, there are intervals in which the availability is almost non-existent. The prevailing wind speed of 7 m/s, and the probability of achieving speeds higher than 17 m/s is almost zero.

The wind power production for each interval was

determined with the help of the software WAsP®, having been considered turbines with a nominal power of 225 kW. Such a turbine was selected considering (i) on estimated consumption of around 360 kWh for 2020, and (ii) access size restrictions. The annual estimated production for the above-mentioned turbine is of 0.561 GWh, which represents an annual production of 2490 hours at the nominal power (NEP's).

The measurement campaign of the solar resource shows that despite its lower potential, its daily availability is higher. Additionally, it is verified that the temperature is proportional to the solar radiation.

The solar energy production for each interval was determined with the help of the software PVSyst®, where a fixed system with a peak power of 1 MWp was considered. An annual production of solar energy for the previous scenario is of 1.47 GWh, which corresponds to a production of 1470 hours at the nominal power (NEP's).

C. Storage Systems

For the case in which a 100% renewable system is required, storage technologies have a preponderant importance, given that they will have to store/provide high quantities of energy to satisfy the inherent intermittency of renewable sources and consumption. Of all the different types of storage technologies analyzed, the technology that shows to be more adequate to the current situation of the island of Brava is a battery system of sodium sulfur. This technology shows a high maturity, and it has the capacity to provide high power during short periods, as well as to ensure long-term energy supply.

D. System to Implement

The conducted analysis of the availability of the wind and power resources, as well as the estimation of the evolution of the demand of electrical energy for 2020 are applied to the calculus of the optimal technical economic conjunction, to assess the needs for the renewable production and for storage that allows to fulfil the energy needs of the island.

The different scenarios of energy mix will be based on a span of one year, in which every energetic need is analyzed in intervals of 10 minutes (range used during the collection of the data in the measurement campaign). For each instant, the balance between the energy produced and consumed is calculated, and the difference between these two variables will be compensated by the storage system. Therefore, in each instant one of the following scenarios is verified:

- Consumption equal to production.
- Consumption greater than production:
 - The storage system has the capacity to provide the energy deficit.
 - The storage system does not have the capacity to provide the energy deficit.
- Consumption lower than the production:
 - The storage system has the capacity to store the energy surplus.
 - The storage system is already at its maximum capacity, and the energy surplus is lost.

For each of the technologies' combination, the LCOE cost is estimated. The main outputs of the calculus include: reliability level of the system, produced energy of each of the sources, stored energy, lost energy, deficit periods, etc.

The final system will be consisting of a solar park, a wind park, a storage system (NaS batteries) and a control system. The control system will have a dispatch order, which will collect and analyse the data related with the state of each technology, and send instructions for the elements of the system, thus securing the continuous work of it. Figure 2 shows the idealized schematic representation and the interaction between the different systems.

Fig. 2. Scheme of the idealized system for Brava Island.

III. APPLIED METHODOLOGY

The main indicator to compare different types of technologies to produce electrical energy is the cost of production during its lifetime, usually known as Levelized Cost of Energy (LCOE). The LCOE allows the assessment of the economic reliability of projects of electrical energy production, as it considers the cost of such a production system, as well as the electrical energy produced during the lifetime of the project. This indicator represents the cost to apply per kWh to ensure every expense (CAPEX and OPEX), that still achieves the profits required by the investors. Its mathematical representation is given by equation 2, in which t is time in years, n is the lifetime of the system in years, r is the return rate, I_t is the initial investment (CAPEX), M_t is the operational and maintenance costs (OPEX) and E_t is an estimation of the electrical energy produced [5-7].

$$LCOE = \frac{\text{Lifetime Costs}}{\text{Energy Generated}} = \frac{\sum_{t=1}^n \frac{I_t + M_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (2)$$

To determine the best combination of power to install of each technology, the implementation costs of several combinations is determined to find the lowest costs that still fulfil the electrical energy consumed by the system. The energy consumed is the balance between the available energy and the energetic needs of the system in each interval. This approach has to do with the fact that the considered technologies cannot vary its production on demand, given that they rely on the climatic conditions, thus penalizing technologies that present a higher deviation between the production and consumption. The optimal combination of power to install of each type of technology will correspond to the solution with the lowest value and LCOE. Given these assumptions, Figure 3 presents the results of solar and wind

power, as well as storing values that guarantee the lowest LCOE value for different renewable penetration rates.

considered to make up for the annual degradation of the solar panels, and that, in this scenario, LCOE would tend to decrease. Considering a service rate of 99.9%, a reasonable value for the electrical energy system of Brava, one would already be improving on the current system, which showed an unavailability of 1% during the measurements campaign. This means an annually reduction from 88 hours to 9 hours.

Fig. 3. Optimized combination for different service rates.

The conjunction of information of Figure 3 and Figure 4 allow the following conclusions:

- Lower values of LCOE are observed when there is inflation.
- As renewable penetration increases, it is preferable to invest in the production of electrical energy, instead of increasing the storing capacity.
- It is more advisable to invest in solar power, rather than in wind power, given its daily predictability. Therefore, with the increase of renewable penetration, solar power to install also increases.
- The waste of energy increases with the increase of the renewable penetration (Figure 4), in a steady way until 99.9%. The extreme case (100%) leads to a sudden increase of wasted energy (it almost doubles when comparing with the 99.9% case).

Fig. 4. Evolution of wasted energy with the increase of service rate.

The oversizing of electrical energy production implies that for a service rate of 100%, the double of the electrical energy would be produced. In the case of an annual unavailability of 0.1%, that excess goes to half. Despite the wasted energy not being considered for the LCOE estimation, it is possible to foresee that it will have a significant impact in case it is

Therefore, the implementation of this project would allow an annual reduction of 862 thousand liters of diesel and, therefore, of 2160 tons of CO₂ emissions.

Figure 5 presents the system behavior during a week, where one can analyze the contribution of each technology to ensure the continuity of the service.

In the case of high wind energy production, the usage of the storing system is low, as the low depth of battery discharge implies. However, a stoppage in wind energy production would generate high depth discharges. The existence of long periods of wind potential makes the solar production responsible for ensuring the service's continuity. The high values achieved by it during the day allow for the storing of enough energy for when there is a deficit in production.

Fig. 5. System evolution to the case of a renewable penetration of 99.9%.

IV. CONCLUSION

With an electrification rate of 100%, the energetic needs of the island of Brava are mostly domestic. That can be verified by the daily reduction between the load diagrams, and by the daily consumption spike observed at the end of each day. Because there are no relevant projects coming up, it's reasonable to assume that the load diagram won't suffer significant changes over the next few years. Therefore, the current estimated TCMA will be used to calculate the consumption for the year 2020.

The current system of electricity production in the island is composed by a single thermal power plant, in which the production costs are high, being linked to the oil price.

The analysis of the renewable energy potential highlighted the seasonality of the wind power, and even though solar's power is inferior, its daily variation proves to be low.

To decide on the storing system, priority was given to technologies with a high power and a high capability to store energy during long periods. Conditions for their implementation were also taken into account. In the end, batteries proved to be the technology that best fits the requirements.

During the evaluation of the power to install for each technology, it was verified that, given the high capex of the storing system, the preferable option is to opt for an oversized production system, instead of using a bigger storing system. The solar power is showed to be advantages when compared with the wind power, given its lower seasonality. This fact was decisive into choice of solar energy over wind energy.

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