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Planning for a 100% renewable energy system for the Santiago Island, Cape Verde

Paula Ferreira[a1], Angela Lopes[b], Géremi Gilson Dranka[a,c] & Jorge Cunha[a]

[a] *ALGORITMI Research Centre, University of Minho, Campus Azurém, 4800-058 Guimarães, Portugal*
[b] *University of Minho, School of Engineering, Campus Azurém, 4800-058 Guimarães, Portugal*
[c] *Department of Electrical Engineering, Federal University of Technology, Parana, Via do Conhecimento, 85503-390 Pato Branco, Brazil*

ABSTRACT

Ensuring the supply of affordable energy, improving energy efficiency and reducing greenhouse gas emissions are some of the priorities of the governments of several countries. The pursuit of these energy goals has triggered interest in the exploration and usage of Renewable Energy Sources (RES), which can be particularly appropriate for island systems as is the case of Cape Verde. This work proposes a generation expansion planning model for Cape Verde considering a 20 years' period. Different scenarios were analysed, each one representing a possible RES contribution for electricity production, reaching a 100% RES share. The results demonstrate that the increase of the RES in the system will lead to an increase in the total system cost. However, a significant decrease in both CO_2 emissions and external energy dependency of the country is projected. The seasonality of the RES resources, and in particular of wind power is shown to be one of the most important challenges for the effective uptake of such a renewable power system. A least-cost solution might be possibly achieved if storage technologies would be considered within the modelling approach (e.g. battery and Power-to-Gas technologies) which would also contribute to accommodate the Critical Excess of Electricity Production (CEEP). While the proposed model allowed already to present some useful scenarios, it becomes also evident the need to expand the analysis by using hourly data and taking into account the sector's integration (e.g. power, heat and transport).

Keywords:

Electricity planning;
Renewable Energies;
Cape Verde;
Scenario analysis;

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1. Introduction

Access to energy is a prerequisite for economic and social development since any productive activity needs energy as a means of promoting competitiveness. This quest for a sustainable energy system is particularly relevant for developing countries, as is the case of Cape Verde.

Cape Verde does not have any known fossil fuel resources, which makes the country totally dependent on imports of petroleum products. Despite the excellent renewable conditions in the country, in 2018 only 20.8% of the electricity produced came from Renewable Energy Sources (RES) [1,2].

On the other hand, Cape Verde still faces the problem of the lack of permanent surface water, since there are scarce rain resources in the country. This natural condition severely limits the possibility of using both hydroelectric electricity and hydro storage. This also leads to additional energy requirements as the country is dependent on water desalination plants. Thus, the high production of electricity from non-renewable sources and the mandatory use of desalination are important challenges faced by Cape Verde electricity sector. All these difficulties result in high electricity and water tariffs which are among the most expensive ones at a global level [3].

*Corresponding author - e-mail: paulaf@dps.uminho.pt

Despite the optimistic prospects regarding the grid integration of renewable energy sources, a series of barriers have been pointed out that may restrict their implementation in the electricity generation process. For many African countries, while the renewable potential is high, its effective integration is often limited due to cost barriers, financing difficulties, the existing policy and regulatory framework, technical issues related to the grid structure but also because of the variable and not fully predictable nature of some RES resources [4,5]. The operationalization of these sources depends mainly on the natural conditions, which often do not follow a pattern close and positively correlated to demand, making the generation of electricity variable, on opposite to traditional sources that provide a controllable and constant energy flow [6].

Painuly [7] and Nasirov et al. [8] argue that, especially for developing countries, the initial costs are the most important barrier to the introduction of these features into the power system. In addition to the high initial investment costs, the lack of regulatory and political frameworks is also highlighted in [9] as a potential barrier, especially for islanded systems. However, the benefits might be higher if there is a good use of RES for electricity generation, and this can be reached at a local level, by improving the social and economic conditions of the regions concerned, and at a global level through of the resulting environmental benefits.

A review of the main challenges associated with RES integration to grid has been recently addressed in Ref. [10]. The impact of using probabilistic weather data to model 100% RES systems is addressed for the La Gomera Island in Ref. [11]. The vulnerability to climate conditions of high RES systems was highlighted in Ref. [12] which also underlined the importance of using different RES technologies in order to take advantage from the complementarity between renewable resources.

This paper addresses the case of Cape Verde electricity system and analyses different electricity generation scenarios for the largest island of the archipelago – Santiago. Recent research has addressed the design of a fully decarbonized electricity system for West Africa countries, by also including the case of Cape Verde [13]. However, although several studies have already addressed the renewable energy planning for the country (see for example [13–15]), to the best of the authors' knowledge, the use of a cost optimization approach to design scenarios combining different technologies to reach a 100% RES system and acknowledging the seasonality of these resources, has not yet been fully explored for the specific case of the Santiago's island. A generation expansion planning model was developed and the specific conditions of the region were analysed, namely the present structure of the power system, renewables potential and intra-yearly variability of demand and natural resources. The challenges related to a possible 100% RES system are debated and future directions for planning and modelling are also pointed out.

The remainder of the paper is organized as follows. Section 2 briefly presents a description of Cape Verde energy system. Section 3 discusses the challenges that emerge in the case of electricity planning for island systems. Section 4 presents the electricity planning model used for Cape Verde. The results are shown in Section 5 and Section 6 draws the main conclusions of the paper.

2. Cape Verde Energy System

Cape Verde's energy sector is characterized by the use of fossil fuels (petroleum products), biomass (firewood) and small expressive use of other renewable energies, namely solar and wind energy [1]. According to the electricity and water operator of the country [2], the total electricity produced at the end of 2018, reached 429.6 GWh, representing an increase of 4.8 GWh (1.1%) compared to the same period on the year before. The total penetration of renewable energy sources in 2018 was 20.8%, an increase of 2.3% compared to the value in 2017 (18.5%). This observed increase was mainly driven by solar power production and to a lesser extent to the increase in wind power energy.

Cape Verde is highly dependent on fuel imports, since it does not have its own energy resources of fossil origin [14]. In 2018, close to 80% of the electricity generated in the country came from fossil fuel thermal power plants [2] which demonstrates the high dependence and vulnerability of the country to oil prices fluctuations [9] with a direct impact on the frequent changes on the price of electricity [16].

If we look at electricity production in recent years, we find that there is an average growth rate of more than 7% per year between 2009 and 2013 [1]. According to the Cape Verde Renewable Energy Plan (PERCV), it was estimated that electricity consumption can double by 2020 compared to 2011 [3]. The intermediate scenario predicts that total electricity demand for the nine islands could reach 670 GWh by 2020, representing a growth rate of around 8% per year over the period 2013–2020 [3]. Although this increase has been moderated in the more recent years, reaching a yearly average value lower than 4.5%, the increasing trend is well evident [2,17–19] driven by the population growth and increasing economic activi-

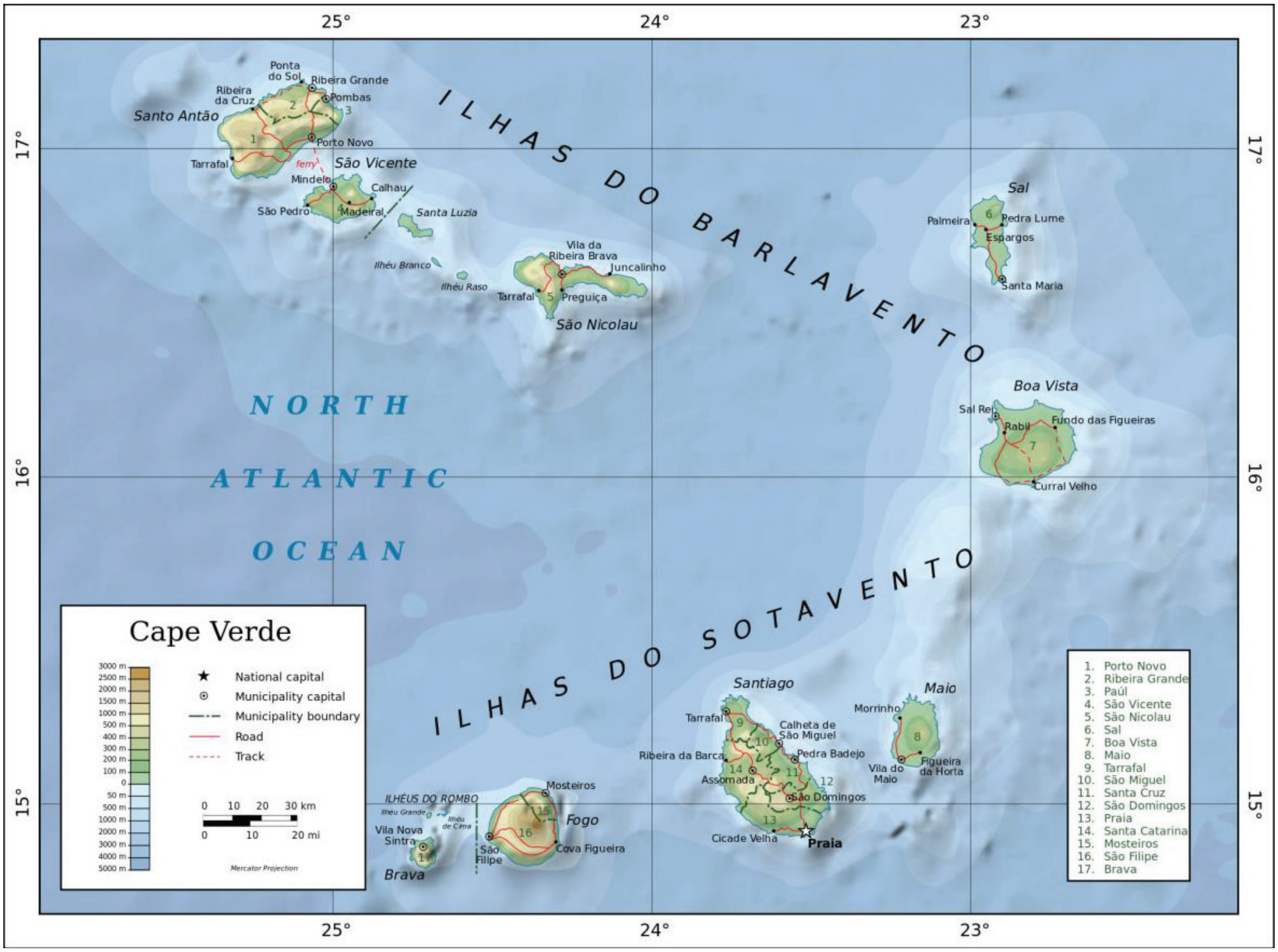

Figure 1: Topographic map of Cape Verde [24]

ties such as the growth of the tourism in the islands. Recent studies, such as [20] also assumed that the yearly growth rates for electricity consumption in Santiago Island could reach a value between 3.4 and 6.8% until 2040.

The integration of renewable resources in electricity generation focuses mainly on wind and solar energy in the country, given the scarce rainwater resources that enable the creation of traditional on-stream hydropower. Only an off-stream pumped storage hydropower plant is being considered to increase renewable energy penetration and dispatching in Santiago's Island [21]. It should not be forgotten that Cape Verde has a strong dependence on water desalination plants, which is a process that requires a significant amount of electricity. In 2018, more than 8% of the electricity generated was used for water desalination related activities as 99.5% of the water supplied to the population came from desalination plants [2]. The particular potential of a hybrid renewable energy system configuration for the better use of desalination plants was concluded in [22]. The real possibility of powering Seawater Reverse Osmosis (SWRO) desalination plants solely with renewable energy has been also highlighted in [23].

Cape Verde is composed of a group of ten islands, nine of are inhabited. Figure 1 illustrates the topographic map of Cape Verde. For the sake of simplicity and as islands are not grid-connected, this study was restricted to the island of Santiago, which is the most populous one and where the capital city is located. The island of Santiago stands out not only for its size but also for being the one with the highest energy consumption, representing in 2018 about 55% of all generation and consumption in the country [2].

Cape Verde faces several challenges in what concerns the energy sector which should be taken into account on the future design of energy policies ([2] and [25]):

- Weak institutional capacity: Institutional capacity and skills within the sector are highly limited, especially with respect to policy formulation and implementation and regulation.

- Weak planning and investment capacity in the electricity subsector: The dependence of a single operator on electricity production given the weak capacity to manage and respond to the increasing demand for electricity.
- The insularity of the national territory: The geography of Cape Verde poses enormous challenges for the sector. Inter-island imports and distribution of small quantities of fuel are highly costly.
- The inadequacy of storage capacity and logistic means: Storage capacity of fuels, as well as logistics, are inadequately distributed between islands.
- Poor electricity production and distribution system: The production capacity and distribution network of electricity and water are inadequate with regard to demand due to the lack of investments and the non-integration of the distribution networks. This situation leads to enormous deficiencies in the energy and water sector, with considerable losses for the population and the economy. The total losses of the electricity sector reached more than 25% of the production in 2018 [2] and represent a barrier to meeting the energy goals for the country [26].
- A weak system of efficiency incentives: The weak institutional capacity facing the energy sector is not conducive to policy development and innovation, resulting in almost no incentives to improve the energy system.
- A weak penetration of alternative energies: Cape Verde has excellent conditions for wind and solar energy. However, despite the favourable conditions, the cost factor has been one of the main barriers to its widespread adoption. Large initial investments give rise to significant financial costs, resulting in higher production costs than fossil fuel alternatives. Combining the resources to achieving a 100% renewable electricity goal in a manageable and cost-effective way remains a challenge in Cape Verde [27].
- Increasing water demand: Forecasts for water demand show a steep increase in the upcoming years [28], in part, due to the pressure from tourism and agriculture but also due to the basic population needs. Providing an answer to these needs is a major challenge for the energy sector given the desalination requirements.
- Lack of awareness on the role of the education system and the media: The need to save energy and reduce dependence on fossil fuels is poorly debated in Cape Verde. The reformulation of school programs and the introduction of awareness-raising activities in the media should be a priority. Oliveira [26] called attention to the leading role on the media to transmit information about energy efficiency and RES in Cape Verde, but also demonstrate that is necessary to carry the message to people in their communities, especially the rural ones.

In fact, the high renewable potential has already motivated studies on the exploitation of these resources for different islands. These studies clearly demonstrated that RES is a promising alternative for sustainable energy supply (see for example [29] for wind power, [30] for wave power, or [31] for rural electrification projects). A fully decarbonized electricity system would also be the most job-rich option among other alternatives [13]. Furthermore, the efficient integration of these technologies would enable Cape Verde to solve the problem of water scarcity with a source of energy that is both environmentally friendly and economically viable. From the point of view of security of supply, for a country like Cape Verde that does not have fossil resources or known reserves, the role of renewable sources is thus essential.

3. Electricity planning for island systems

Traditional energy resources in islands are usually limited and highly dependent on natural surroundings, including conditions affecting possible renewables utilization. These characteristics might be partially explained by their isolation and small size characteristics [32]. In fact, for most of the world's islands and remote areas, imported fuel remains as the main source of primary energy [9,33,34]. Therefore, the use of renewable energy may be of great assistance especially for these island power systems [9,35].

For many small islands developing states, fuel import bills account for about 20% of annual imports and between 5% to 20% of GDP [36]. This finding is also corroborated by [34] claiming that some islands spend more than 30% of GDP on fuel imports. The cost of electricity in the islands is usually significantly higher compared to the continental regions [37] due to the inherent difficulties in supplying these localities. Oil shortages occur frequently in the islands, as transportations are strongly affected by weather conditions [38]. The potential of upgrading autonomous diesel-based by solar-battery-diesel-based electricity systems has been globally investigated by [35] by also concluding that the average LCOE would be reduced from 0.35 ct/kWh to 0.12 ct/kWh for the specific case of the Cape Verde power system. Island countries have structural disadvantages linked to insularity, the persistence of which seriously undermines their economic and social development [39]. It should be noted, however, that these regions produce only a small fraction of the global GHG emissions. However, they are among the most vulnerable regions in the world to the effects of climate change, such as rising sea levels and extreme weather conditions [38].

The high costs of submarine transmission cables constitute the main barrier in the connection between the islands and the mainland, as well as between the adjacent islands such as supported by [34,40]. Therefore, the supply of electricity on the islands is generally unstable [40]. In addition, most rural areas are not covered by electricity supply grids and distributed diesel generators are often used for a few hours at night. Since the fuels are usually scarce in these places, the supply of electricity is often affected and even disrupted.

The use of renewable sources in the generation of electricity can be particularly appropriate for islands and remote areas. Amaral [41] reported that the integration of RES in small islands energy systems has several advantages, notably at an economic level since its high investment cost is offset by the small size of the system and the reduction in the import of expensive fuel. Accordingly, Segurado et al. [15] argue that the integration of renewable sources into the energy system on small islands has both economic and environmental advantages since fossil fuels can cause serious damage to the ecosystem and natural habitats.

In fact, there has been an increasing number of publications on the possibility of reaching 100% renewable islands in several regions. A few recent examples based on long-term modelling and scenario analysis include the case of the Reunion [42], Ometepe [43] and the Mediterranean Islands [44].A set of options for achieving a 100% RES for Mauritius island (2050) has been also explored by [45]. Examples of recent research which also focus on achieving a 100% RES using the EnergyPLAN model includes the case of Canaria (2030) [1], Åland (2030) [2] and Wang-An islands [46]. The REMix model has been also applied for the case of Canary Islands (2050) [47]. The Hybrid Optimization Model for Electric Renewables (HOMER) has been also considered for the assessment of fully decarbonized pathways in islands such as for the case of Agios Efstratios [48], St. Martin [49] and Prince Edward islands [50]. Overall, the studies showed the relevance of this RES pathways to reach a low carbon system but also highlighted the need to integrate other sectors and solutions to reach the best solutions well fitted to local conditions [32].

On the other hand, for developing countries or isolated areas/islands, the production of RES-based energy imposes some cost barriers. In fact, the use of renewable energy for the generation of electricity does not only have to deal with difficulties stemming mainly from the irregular nature of most existing renewable sources but also from the investment required for renewable energy technologies. According to [51], the consumers tend to prefer a lower initial cost than a lower long term operating cost. However, [52] argued that for renewable penetrations up to the optimal points in the range of 40–75% there is an evident cost reduction which is only compromised for larger RES shares, in some cases, given the requirement for storage becoming more significant. The increasing importance of batteries application has been also highlighted by [35] especially when the share of solar PV is higher than 45% of the overall power system's capacity.

4. Planning model for Cape Verde

The proposed planning model was coded in GAMS (General Algebraic Modelling System), a programming language that allows to define and solve an optimization problem through integrated commercial solvers. The model resulted in an integer linear problem and the CPLEX solver was selected to obtain the numerical results. The original model of [53] had to be adapted for Santiago's island, as it was initially designed to the Portuguese case. In the newly formulated model, only three energy sources were considered to be added to the electricity system of Santiago, namely biomass from urban solid waste, and wind and solar power which were included according to the island's potential. The selection of these three resources is justified by the country priorities and strategic plans which have already identified these options and the priority areas for development of these power plants in the island [2]. Equation 1 shows the objective function whereas Figure 2 provides a more comprehensive overview of the proposed planning model, including the objective function, main restrictions and main outputs.

$$\sum_{t \varepsilon T n \varepsilon N} \sum \left[\left(IC_n \frac{j(1+j)^{lt_n}}{(1+j)^{lt_n}-1} + CFOM_n \right) Ip_{n,t} (1+j)^{-t} \right] + \sum_{t \varepsilon T m \varepsilon M_i \varepsilon I} \sum \sum \left[(CVOM_i + F_i + EC \times CO_{2i}) P_{i,m,t} \Delta_m (1+j)^{-t} \right] \quad (1)$$

In Equation (1), T is the planning period (years), N represents the new units to be included, M are the months of the year, I denotes all plants included in the model, Ic_n (€/MW) is the investment cost for each of the n new plant, j is the discount rate (%), *CFOM* (€/MW) are the fixed O&M costs of the n plants, Ip_n (MW) is the installed power of a new plant (n) in year t, CVOM (€/MWh) are the variable O&M costs for each i plant, F_i (€/MWh) are the fuel costs for each i plant, EC (€/ton) is the emission allowance cost for the CO_2 emissions, CO_{2i} (ton/MWh) is the emission factor for each i plant, $P_{i,m,t}$ (MW) is the monthly production of each i plant during the planning period and Δ_m is the number of hours of each month.

The parameters used in the optimization problem include the expected monthly demand for the next 20 years, availability of energy sources, the estimated cost of CO_2 emissions licenses, lifetime, fuel cost, the investment and O&M's fixed and variable costs for all technologies. These values were obtained from international literature and reports for the country [3]. The input data used for the existing [54–56] and new generating units [3,55,57–60] are presented in Table 1 and Table 2 respectively. The direct CO_2 emissions (i.e. the emissions at the point of production) are considered only for the existing diesel units (0.24 t/MWh) and the average price of CO_2 allowance is set to 25 €/t based on [61]. The capital costs[1] for solar power were estimated

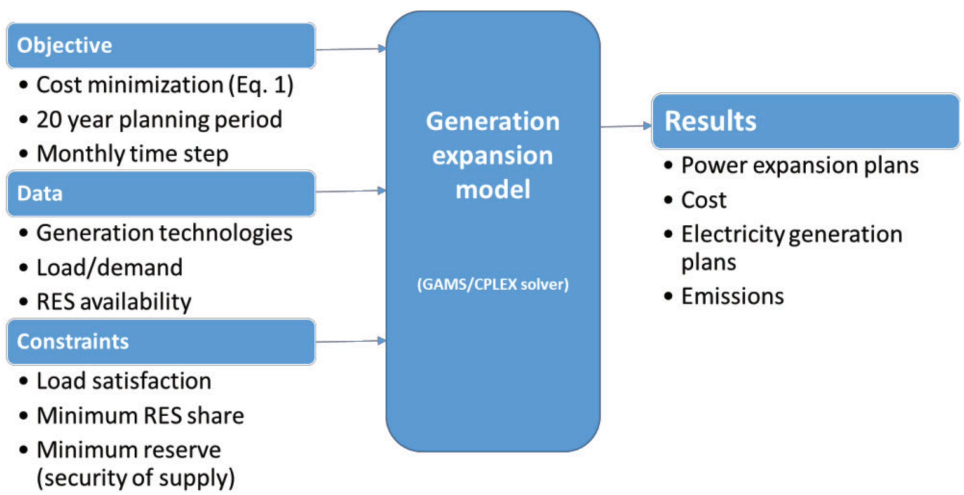

Figure 2: Overview of the proposed planning model

Table 1: Input data for the existing generating units

Source	Fuel cost (€/MWh) [2,62]	Variable costs (€/MWh) [55,57]	Existing installed power capacity (MW)
Diesel	120	3	69.96
Wind	0	5	9.35
Solar PV	0	0	5

[1] One Euro (€) is equivalent to 1.11 United States (US$) Dollar (June 03, 2020)

Table 2: Input data for the new generating units

Source	Expected lifetime (years) [3,57]	Fuel cost (€/MWh) [55]	Capital costs (million €/MW) [58–60]	Fixed O&M costs (€/(MW.year)) [57,59]	Variable O&M costs (€/MWh) [57,59]
Biomass	25	7	4.34	114,984	4.2
Wind	25	0	1.75	43,750	5
Solar PV	25	0	1.32	33,000	0

based on Ref. [60] by taking into account a cost level around 1200 US$/kW for large-scale PV and 2000 US$/kW for smaller scale rooftop systems assuming that 2/3 would be from large-scale and 1/3 for smaller roof top systems (by volume) which would lead to an average cost level of about 1467 US$/kW. The average capital cost is also considered for wind power and biomass based on Ref. [57] and [58] respectively. The fuel costs for diesel was estimated based on the average fuel consumption in g/kWh [2] and on the average fuel cost in €/kg [62].

The average monthly electricity production from photovoltaic plants (kWh) was obtained through the Photovoltaic Geographical Information System (PVGIS), a site that allows access to solar radiation and temperature data and photovoltaic performance evaluation tools to any place in Europe and Africa, as well as for a large part of Asia [63,64].

On the other hand, the monthly wind speed of each of the identified renewable energy development zones [3] was obtained from the site of NASA Langley Research Center through the Surface meteorological and Solar Energy (SSE) data [65]. The power curve of the Vestas Turbine-V52, was used to estimate the expected wind power output.

Table 3 summarizes the monthly availability of RES on the island of Santiago as implemented in the model.

Table 3 puts in evidence the high seasonality of the RES resources, which essentially has to do with the natural conditions of the island. This variability is most evident for the wind since the values vary between 6% during the summer period and more than 40% for the winter period. The biomass power output is assumed to be stable since it does not depend on the weather conditions. The variability of RES is undoubtedly the main difficulty of integrating them into the grid to ensure the security of supply. As the island is a closed system, a reserve margin of 10% was considered [66].

Table 3: Monthly availability of RES power in Santiago

Month	Biomass	Wind	Solar
Jan	70%	43%	14%
Feb	70%	31%	18%
Mar	70%	26%	22%
Apr	70%	27%	22%
May	70%	26%	23%
Jun	70%	20%	21%
Jul	70%	6.9%	19%
Aug	70%	5.9%	18%
Sep	70%	9.8%	18%
Oct	70%	18%	18%
Nov	70%	23%	16%
Dec	70%	30%	15%

Based on all the data presented, we simulated and optimized three different scenarios:

– Business-as-Usual (BAU), corresponding to the base scenario departing from 2015 values and assuming no RES restrictions;
– Renewable scenario (100RES), corresponding to a 100% RES.
– Renewable scenario (Div_RES), corresponding to a 100% RES system with diversified sources.

5. Results

The expected average cost, average CO_2 emissions for the entire planning period and RES share on the last year of the planning period (year 20), for the three scenarios, assuming a discount rate of 5% per year are illustrated in Table 4. The new installed power capacity over the entire planning period and the capital, fixed O&M and variable O&M costs for each power source are illustrated in Table 5 and Table 6, respectively.

It can be seen from the data in Table 4 the increasing trend for the average system's cost, mainly due to the increased installed capacity for the RES scenarios

Table 4: Results from the planning model for the average cost, average CO_2 emissions and RES share

Scenario	Cost (€/MWh)	CO_2 (t/MWh)	RES share (year 20)
BAU	45.8	0.027	89%
100RES	48.7	0	100%
Div_RES	78.4	0	100%

Table 6: Results from the planning model for the capital, fixed O&M and variable O&M costs

	Capital (%)	Fixed O&M (%)	Variable O&M (%)
BAU	59.5%	21.1%	19.4%
100RES	72.7%	25.7%	1.6%
Div_RES	71.1%	25.1%	3.7%

Table 5: Results from the planning model for the new installed power capacity for the entire planning period

Scenario	Diesel (MW)	Biomass (MW)	Wind (MW)	Solar PV (MW)	Total (MW)
BAU	0 (0%)	6.7 (2%)	0 (0%)	360.5 (98%)	367.2 (100%)
100RES	0 (0%)	6.7 (1%)	0 (0%)	479.5 (99%)	486.2 (100%)
Div_RES	0 (0%)	6.7 (1%)	288.8 (43%)	372.3 (56%)	667.8 (100%)

(see Table 5 and Table 6). On the other hand, CO_2 emissions would be reduced to zero in the case of a 100% RES share could be reached. A simulation for a discount rate of 10% per year was also conducted which showed that the results were robust and the optimal scenarios and generation mix remained close to these results. Table 6 illustrates the higher expected decrease in the variable O&M cost share for 100% RES scenarios compared to scenario BAU.

For scenario BAU, solar power would represent 81% of the total electricity production in the last year of the planning period, followed by diesel (11%), biomass (5%) and wind (2%). As for the 100RES scenario, wind power would represent only 2% of the total electricity production and biomass would reach 5% in the last year of the planning period. Solar power would represent 93% of the total electricity production. This result comes from the cost minimization approach for the 100RES, which favours solar power given the high availability of the resource on the island. These results seem to be consistent with other research which highlighted that solar PV is found to have a huge future potential and it might provide up to 85% of the overall electricity supply by 2050 in West Africa's future power system [13].

In fact, as the model assumed monthly time steps the intra-daily variability of the resources and demand have not been considered. In order to partially overcome this limitation, an additional scenario was tested, now imposing a diversified structure for the renewable power system. The Div_RES scenario will result in a higher cost but ensures that wind power will have a significant role in the power generation mix. For the last year of the planning period, 50% of the total electricity production would come from solar power, followed by wind power (47%) and biomass (3%) for Div_RES scenario.

Figure 3 compares demand and monthly production by technology for the last planning year (year 20), according to scenario BAU. Since there are no major temperature variations in Cape Verde, demand for electricity is relatively stable throughout the year, with a small increase during summer which may be justified by the touristic activities. However, Figure 3 illustrates the variability of some energy sources, as a consequence of seasonality. The low production of electricity from wind energy is evident in the months of July, August and September due to its weak potential in these periods. On the other hand, production from solar energy and biomass is practically stable, with only a small variation. A 100% RES system would be possible to be reached between February to June, but for the remaining months the system would resource to diesel. During these months a situation of excess production could in fact be expected.

Figure 4 shows the results of the 100RES scenario. The total electricity production is considerably higher than for BAU with excess production in several months of the year. The lower reliance on wind power is mainly justified by its low electricity generation potential during the summer months. Solar power would then supply most of the electricity needs, but the practical implementation of such a scenario would bump into technical problems related to the night period and the need to complement the system with storage technologies. As those are not considered in the model, a

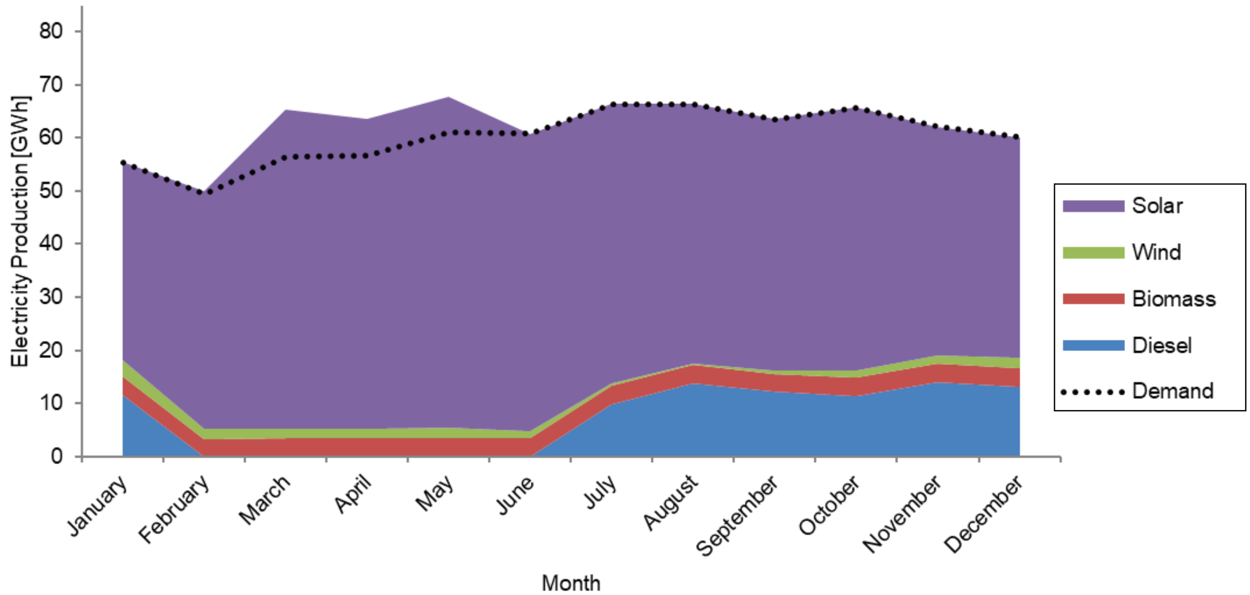

Figure 3: Monthly electricity production for Santiago's island in the BAU scenario in year 20

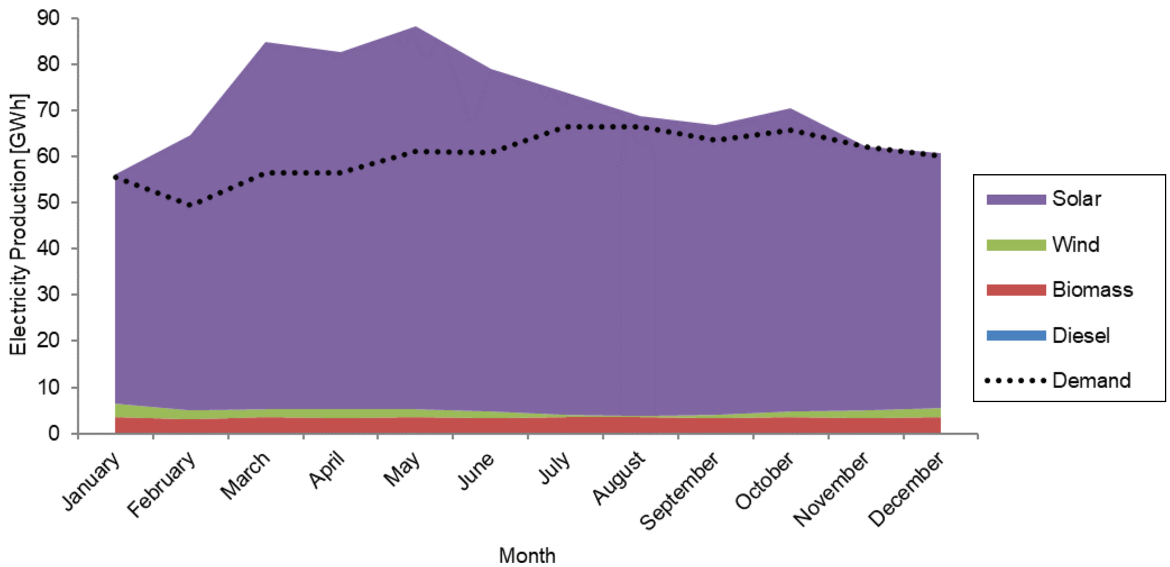

Figure 4: Monthly electricity production for Santiago's island in the 100RES scenario in year 20

diversified scenario such as the one presented in Figure 5 is more realistic and still theoretically sound. Although recognizing the limitations brought by this assumption, as the system stability for all hours of the year cannot be shown, the use of this monthly model can be useful to obtain a limited set of possible optimal solutions constrained by political or legal requirements or policies. These limited set of solutions may then be more easily refined using hourly optimization or simulation tools to compute accurate cost, emissions and operational parameters (see for example [50] and [70]).

Figure 5 shows the results of the Div_RES scenario and puts in evidence again the seasonality problem. To avoid power deficit, the system would require a high value for RES installed power capacity leading not only to higher costs but also to excess production in almost all months of the year and this would result in curtailment of renewables to avoid frequency stability problems (see [67] for more

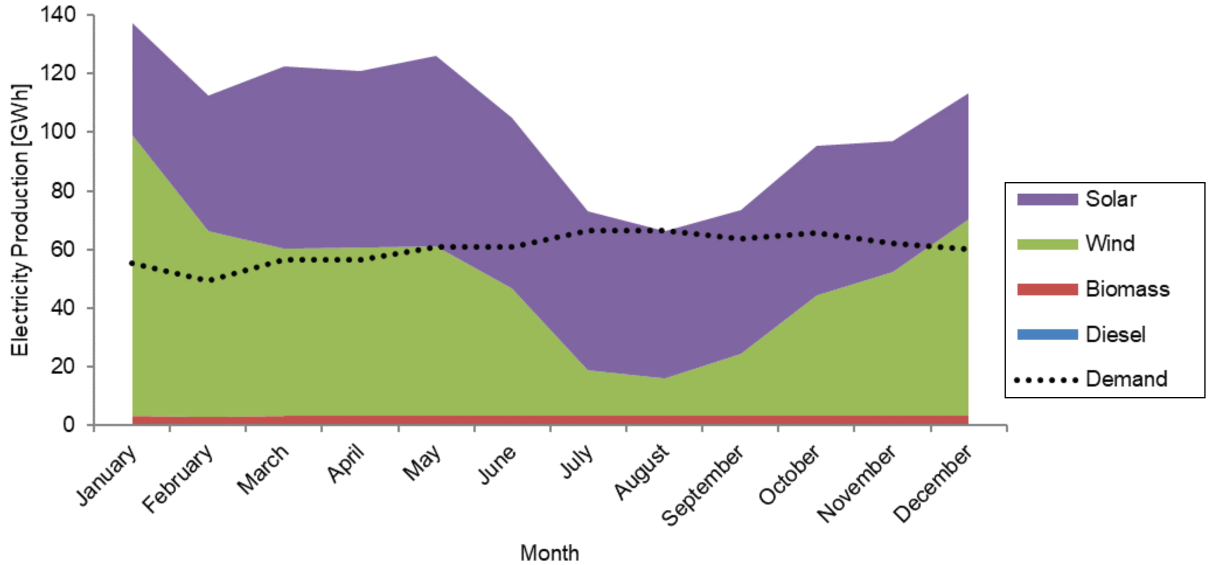

Figure 5: Monthly electricity production for Santiago's island in the Div_RES scenario in year 20

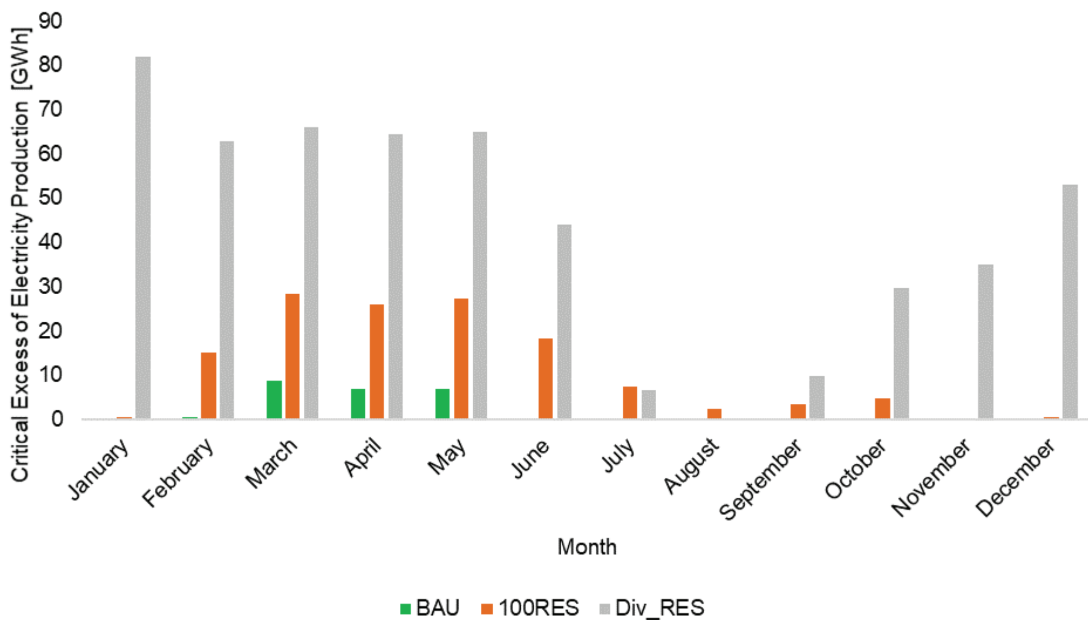

Figure 6: Monthly critical excess of electricity production for Santiago's island in all scenarios in year 20

details). In fact, the system would be dimensioned by the worst month (August) which present a situation of low wind availability with higher demand requirements. Moreover, the existence of Critical Excess of Electricity Production (CEEP) is much higher than for the 100RES for most of the months which in our case would be translated in curtailment since no storage is considered. These findings might be partially associated with the wind seasonality as solar resource tends to be much more stable throughout the year. However, a least-cost solution might be possibly achieved if storage technologies would be considered within the modelling approach (e.g. battery and Power-to-Gas technologies) which would also contribute to accommodate the CEEP. The CEEP for all scenarios is illustrated in Figure 6 for each month of the last year of the planning period. The integration of storage systems, power to heat, power to gas and power to mobility has been recently addressed by [68] with a particular focus on the future competition on excess electricity production from RES. In [69], the role of wind, solar and storages technologies is addressed across power, heat, transport and desalination sectors for Chile. The use of storage technologies for the Island of Bonaire is investigated by [70] with a particular focus on supporting high shares of variable renewable energy.

Previous research has found that the grid dispatch flexibility might increase using curtailment with [71] and without [72] storage. The authors of [73,74] also found that the use of curtailment would reduce the required storage system's capacity. The curtailment-storage-penetration nexus concept has been recently addressed by the authors of [75] which provided empirical-based evidence that power systems which are designed with curtailment are likely to cost less than the ones which are designed without curtailment. At this point, it is worth mentioning our current model limitations. Our approach does not take into account the use of hourly data and storage technologies, for example, which is precisely a further step to be addressed in future research to provide a holistic assessment for achieving a fully decarbonized energy system in Santiago's island power system. Previous research revealed, for example, that the use of both hourly modelling together with storage technologies would result in lower levels of curtailment [76]. The authors of [76] addressed a 100% RES for the Åland energy system using the EnergyPLAN modelling tool using hourly data and concluded that curtailment of wind and solar power would be around 3.5% of total electricity production.

A comparative analysis of the analysed scenarios clearly shows that different RES resources can complement each other: solar power tends to be more stable during the year, but show a high intra-daily variation; wind power does not suffer from the day-night problem as solar, but the difference between summer and winter months is remarkable; biomass allows for the storage of the resources and can be used then to balance production and contribute to base load capacity [77]. The possibility of using storage technologies and/or demand-side management strategies would be of great benefit for such a system and should be considered on future studies for the country as proposed in the next section.

6. Conclusions

This study intended to contribute to the debate on the possible increase of the integration of renewable energies to promote progress towards a just energy transition in Cape Verde power system. In this context, a model of electricity planning was presented to support the long-term strategic decision, taking into account the need to reconcile objectives of minimization of costs with the constraints of the system. The intention was to formulate, in particular, an analysis of the integration of renewable energies, taking into account the potential of Cape Verde, the seasonal availability of these resources, costs and electricity consumption prospects based on the annual forecasts for a period of 20 years.

The analysis allowed to compare the demand with the monthly electricity production, which highlighted one of the major challenges to reach a renewable electricity system, namely the high seasonality of the RES resources. The seasonality of wind is particularly remarkable which compromises electricity production and the capacity to respond to demand during summer. Additionally, in the winter months, critical excess of electricity production is evidently making it essential to analyse possible ways of minimizing this unused electricity.

While the proposed model allowed already to present some useful scenarios, it becomes also evident the need to integrate short-term issues related to intra-daily demand or availability of resources on the generation expansion model. The results are significant as they indicate that a 100% RES scenario would be possible even with already existing technologies but demonstrate also the challenges and limitations which should not be overlooked. As such, while the proposed energy transition is possible from a technological standpoint, economically, is still limited given cost and even organizational restrictions. These first results show that a high RES system is theoretically possible, but the high cost of the technologies and their variability can result in a prohibitive cost increase for a country which is one of the poorest and smallest island developing countries in the world. However, these costs should be looked with cautions as modelling improvements and the inclusion of additional technologies (e.g. storage) can help to design less cost intensive strategies for a 100% RES system.

This calls for new modelling approaches and opens avenues for further research for the case of Cape Verde. In particular, it is worth to highlight some pathways for the design of energy scenarios, strategies and policies for the country:

- The expansion of the planning model or coupling with an hourly approach to better account for both seasonality and intraday variability, as debated in [78] for the Portuguese case.
- The sector's integration (e.g. power, heating/cooling and transport) would be also further

explored. A theoretical potential to reduce curtailment might be achieved by this sector's integration [76]. The authors of [79] identified a great potential of sector's integration in reducing the storage size. The use of HOMER Energy or EnergyPLAN modelling tools would be employed for this task to model Santiago's power system.

- The inclusion of storage technologies in future versions of the planning model, taking into account the specifications of the system in question characterized by insularity, high RES resources seasonality and increasing electricity demand. These could include electric and thermal storage systems but also Power-to-Gas technologies. The work of [29] already called attention to the need to invest on energy storage systems for mitigating the wind intermittency and minimizing curtailment of wind for higher levels of wind penetration in Santiago island, Cape Verde. The importance of storage for solar PV systems has been also highlighted by [80] for Finland. The role of storage with a focus on Power-to-Gas and long-term storage technologies has been reviewed by [79] which concluded that as more power options may be considered to support the intermittent characteristics of sources, the lower would be the required storage.
- The possibility of increasing the level of adoption of emerging energy technologies, such as wave energy resources given the considerable potential of the resource [30] and its integration on the cost optimization model may be also addressed in further research. However, costs of renewable technologies still remain uncertain for the future [81] and the projecting future cost developments may require different approaches able to deal with risk and uncertainty in energy modelling [82].
- The possibility of focusing on distributed electricity generation technologies in the form of renewable-based microgrids was debated in [27] and should be considered in the planning model, along with off-grid electrification projects [31], demand-side options, and technologies requiring the involvement of the consumer (e.g. electric vehicle). Although this may imply significant investments and shift on the energy policy status quo, it will expedite the transition process and will contribute to reducing the amount of losses in the system.
- The use of future demand-side management strategies may also contribute to the operation of a fully decarbonized electricity system, especially during low renewable resources availability times. The shutdown of desalination plants could be implemented by using a direct load control, for example [83]. However, the authors of [84] investigated the role of desalination plants in a 100% renewable energy context for Saudi Arabia and highlighted a relatively low flexibility potential of desalination plants compared to the combination of solar PV and battery storage systems, for example.
- The inclusion of a sustainability perspective on the planning approach, which would go beyond carbon emissions but would also recognize the need to include social externalities that may come from the RES development are particularly relevant on such a still developing country towards a just energy transition.

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