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# Evaluation of the energy transition roadmaps in islands: Cape Verde Case Study

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**Abstract.** This paper explores the potential pathways for achieving total decarbonization in Cape Verde using the EnergyPLAN software. This research focuses on the unique challenges and opportunities faced by small island developing states (SIDS) in transitioning to renewable energy sources. Cape Verde, with its ambitious goal of 100% renewable electricity, serves as an ideal case study due to its diverse energy resources and the need for sustainable development.
By analysing multiple scenarios, the research aim to identify optimal pathways for achieving a fully decarbonized energy system in Cape Verde. The findings highlight the importance of tailored energy policies, international cooperation, and investment in renewable energy infrastructure to overcome the challenges of energy transition in island contexts.

**Key words.** Energy transition; Cape Verde; EnergyPlan.

## 1. Introduction

In the context of the ongoing energy transition, a broader perspective is essential to move beyond the focus on electricity and towards integrated systems [1]. The growing interest in decarbonizing global energy sectors, such as transportation, is leading to increased electrification, which presents both challenges and opportunities for power systems in managing and accomplish demand. The rising demand for power implies more generation, including a restructuration on transmission and distribution networks [2].
Islands face additional changes in the decarbonization due their unique characteristics, as their heavy reliance on external energy imports, and the lack to the connection to mainland. Also, their small size limits economies of scale and strains their economic resources, sometimes implying lack industrialization, which shapes their demand profile and restricts the available sources of demand response, with the notable exception of desalination. This energy-intensive process typically represents a significant consumer load, and its importance is expected to grow in the face of the global water scarcity crisis in the coming decades [3,4]. Moreover, water desalination is an important aspect to consider in the current water demand and therefore, in the energy requirements Also the introduction of the electric vehicles can lead to significant impacts in the energy consumption [5,6].
The renewable transition in various archipelagos, such as the Azores, Canary Islands, Madeira or Cape Verde, where renewable energy sources were prioritized to reduce fossil fuel imports, transform these territories living laboratories for the renewable transition, supported by investments from the European Union [7–13]. Consequently, research conducted on these islands provides cost-effective insights into policies, technologies, and methods that can later be applied to continental power systems [14–17].
Therefore, bottom-up energy planning roadmaps are required to identify the most appropriate energy mix for a specific region, where these roadmaps are framed as optimization problems aimed at minimizing the costs of investment and operation for the electric system.
In this study, we utilize the EnergyPlan [18] software to shift the focus from purely electric planning to integrated energy system planning, providing different roadmaps to achieve the decarbonization goals in the island of Santiago, in Cape Verde as our case study, due to the local government's current objective of achieving a 100% renewable energy system by 2050, alongside the ongoing electrification of road and maritime transport through electric vehicles and hydrogen vessels [19].

## 2. Methods

### *A. Modelling*

Certain characteristics of EnergyPLAN [20], which align closely with the fundamental principles of this research, make it an excellent tool for this study. EnergyPLAN enables empirical modelling of an energy system and conducts hourly simulations over a one-year period. This software was specifically designed to implement the Smart Energy System concept, allowing for the simulation of the entire energy system and the interconnection of various sectors. Another significant feature of EnergyPLAN relevant to this study is its relatively quick capacity to model and simulate new scenarios, including renewable energy systems, conventional generation, energy storage and $H_2$ among different features. The approach outlined in this research necessitates many simulations to identify optimal scenarios, making computing time an important consideration (Fig.1).

EnergyPLAN simulates the operation of energy systems on an hourly basis for various sectors such as electricity, heating, cooling, industry, and transport. This fact allows to investigate the energy flows and interactions within the system as a whole.

We have defined multiple scenarios for analysing alternative energy strategies and policies. In the scenarios we have included variations in the introduction of renewable energy, energy efficiency of the technology and trends, and flexibility measures like demand response and energy storage. EnergyPLAN employs two simulation levels: (i) an economical optimization, taking into account the available technology and with the adequate analysis of the CAPEX and OPEX, obtain the most economical suitable scenario and (ii) a technical analysis among the different available technologies to minimize the use of conventional technologies, enforcing the use of renewable energies and storages technologies. This mode has been used along this research. Both modes employ various simulation strategies in the modelling of electricity demands, production, fuel distribution, and individual heating. This allows for a detailed, precise description of the energy system behaviour under different conditions.

This tool provides detailed output results in the form of energy consumption, production, emissions, and costs. These can be used to compare scenarios and identify the optimal strategies for achieving sustainable energy systems. However, this software presents some limitations, mainly due to the accuracy of the simulations, that heavily relies on the quality and availability of input data. Incomplete or outdated data can lead to less reliable results.

Even when EnergyPLAN allows for the creation of various scenarios, it may not capture all real-world complexities, such the software might not fully account for unexpected changes in technology adoption rates or policy shifts. In the particular case of this study, the implementation of the recommendations from EnergyPLAN simulations often requires significant technological advancements and financial investments. This can be challenging for regions with limited resources.

Finally, it is worth to mention the effectiveness of the simulated scenarios depends on supportive policies and regulatory frameworks. Without appropriate policy support, the practical implementation of the scenarios may be hindered.

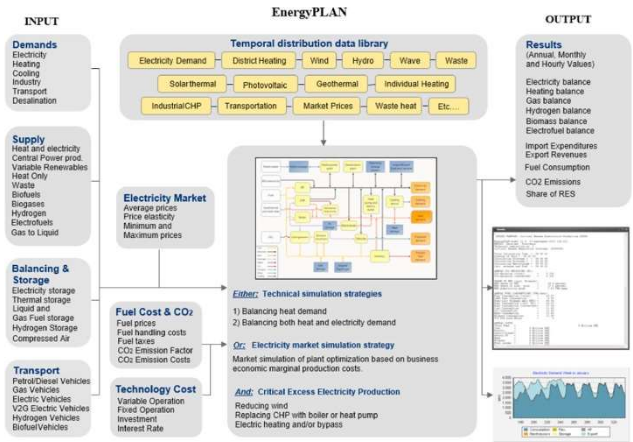


Fig.1. EnergyPlan software scheme [20].

*B. Santiago Island*

The Cape Verde archipelago, conformed by 10 islands, is situated in the Atlantic Ocean approximately 600 km from the African mainland. With a population of around 540,000 distributed across 9 islands, Cape Verde has a distinctly rural character due to its level of industrialization. Despite having excellent solar and wind resources, Cape Verde heavily relies on imported fossil fuels. The government is working to change this through various regulations aimed at improving energy access, integrating renewable energy sources, and decarbonizing transport, though progress has been limited, with an initial goal of achieving 100% renewable energy by 2020 resulted in only 18% by 2012. Currently, renewable energy rates fluctuate between 20% and 25%, largely due to the grid's infrastructure.

Key technical challenges identified include voltage and frequency stability, short circuit capacity, and inertia as limiting factors to increase the renewable energy penetration. Additionally, the significant distances between the islands and the deep waters hinder their interconnection.

Our focus is on Santiago, as it is home to 56% of the population, accounts for 58% of total demand, and has the greatest potential for implementing demand response strategies due to its level of industrialization. Thus, Santiago serves as a highly relevant case study, exemplifying a warm island region [19].


Fig.3. Santiago Island, Cape Verde.

The current energy mix of Santiago Islands is depenging, principally to the fossil fuels, which represents

85% of the electricity production, accompanied by solar and wind, representing the 3% and 12% of the total mix respectively.

Table I. – Current power plants [19].

| | Maximum power (MW) | Minimum power (MW) |
|---|---|---|
| Diesel | 98.7 | 2 |
| Wind power | 9.4 | 0 |
| Photovoltaic power | 4.4 | 0 |

*C. Scenario modelling*

Three scenarios have been used to analyse the possible roadmaps. The first scenario has been a Business as usual (BAU), used as baseline to analyse the current tendencies, where due to operational constrains in isolated systems, renewable energy must be limited to 20%, and they are not allowed to provide spinning. reserve.

The policy-driven scenario, with the aim to achieve the 100% renewable energy in 2050 and finally an economical optimized scenario without limiting renewable penetration and allow them to provide spinning reserve.

## 3. Results and discussion

Using the obtained data from the software, the distribution of electricity generation in the BAU scenario remains consistent with the current tendence observed dung the last 5 years, primarily due to the imposed upper limit of a 20% renewable energy share, which necessitates fossil fuel generators as the predominant source. In this point, the results indicate an energy surplus, indicating the storage systems could play a crucial role in maintaining reserve balance, particularly in the final years when renewable installations are continuously being installed.

Emissions are strongly correlated with the energy mix, and they exhibit a slight stagnation during the initial four years, followed by exponential growth in accordance with the load level, that will increase due to the population grown and the developing of the industry.

The electricity generation distribution in BAU is nearly identical for the current mix, but surplus energy will be achieved and therefore, renewable energy curtailments without the inclusion of the storage systems.

The policy driven scenario, where the government has established the target of achieving 100% renewable energy sources is rapidly accomplished during the first 5, following the decommissioning of fossil fuel generators, where the electrical system is based on a combination of photovoltaic wind and the inclusion of hydroelectric power stations. The maximum capacities for hydro and solar are reached during the first decade leaving the wind power as the unique possibility to accomplish the energy demand, in combination with battery energy storage systems.

Finally the optimal scenario indicates the non-policy driven grown of the renewable energies could bring certain curtailments during the year, achieving the 40% of the total energy produced by renewables, even when they are allowed to provide reserve and flexibility is integrated in the planning.

It is noteworthy that the expansions occur quite gradually, except for the hydroelectric power station capacity. The energy mix is quite similar across all three scenarios. It is important to note that the achieved renewable energy penetration reaches punctually 96%, despite not imposing any specific constraints in this regard.

The limitations and potential sources of error in this study are primarily related to the assumption of a deterministic formulation and the possibility of erroneous data. Consequently, the analysis should be approached as a sensitivity analysis of various scenarios, exploring how different policies, demand fluctuations, and price evolutions would impact the system configuration. Generally, the results for different cases within a particular scenario can be considered robust if they yield similar technological configurations with varying installed capacities. However, significant changes in the overall topology may raise concerns.

Table II. – Obtained results for 2050.

| | BAU | Policy driven | Optimal |
|---|---|---|---|
| Diesel (MW) | 81 | 0 | 22 |
| Wind power (MW) | 41 | 517 | 10 |
| Photovoltaic power (MW) | 38 | 483 | 398 |
| Battery storage capacity (MWh) | 60 | 40 | 0 |
| Hydropower (MWh) | 100 | 1500 | 1500 |

Table II presents the final configurations for each scenario and load growth case. Minor differences are observed in the BAU scenario, where the effects of the renewable penetration limitation are noteworthy. For instance, fossil fuel units dominate the system evolution instead of being gradually phased out over time. Interestingly, battery energy storage systems appear in all cases at an early stage, while hydroelectric power stations are kept to a minimum due to the reduced necessity for seasonal storage compared to short-term reserve provision, given the dispatchability of diesel generators.

In the policy-driven scenario, power requirements surge as the maximum allowed. In this scenario, energy storage systems play a crucial role, with both batteries and hydropower representing significant installations.

Optimal scenario reveals that the demand growths rapidly as the remaining lifetime of the existing thermal units, estimated in 12-15 years. Thus, such buffer period facilitates clearing part of the uncertainty regarding additional generation installation as most of these units are only required part of the simulated time.

When planning for a fully renewable system, there are always questions regarding stability, inertia, and reliability. In this work, such issues are tackled based on significant reserve requirements, and penalizing renewable energies uncertainty in favour of other dispatchable resources.

In addition, there is a significant amount of work available in how to provide stability and other grid services such as frequency support with power-electronic-interfaced devices. For the Cape Verdean system, the inertia has been explored during a progressive renewable transition up to 60% penetration [19,21].

## 4. Conclusion

Islands represent ideal real-world laboratories for renewable energy integration and the transition towards Integrated Energy Systems due to the constrains of being isolated electrical systems. Research conducted in these environments can be easily scaled and transferred to global power systems, with the availability to test several decarbonization roadmap, technology deployment and new procedures. This work has proposed an optimal model with a 20-year horizon and hourly resolution, using Santiago, Cape Verde as a case study. This is particularly relevant for warm regions of the world. The objective function minimizes investment, maintenance, operation, and emissions across three different scenarios: Business-as-Usual, policy-driven and Optimal.

The BAU scenario, formulated as a Generation System Expansion Planning model, maintains the current operational approach, limiting renewable energy penetration to around 20% and not allowing renewable energy source-based reserve provision. The policy-driven scenario, represents the current government strategy, imposing a minimum of 50% and 100% renewable energy by 2030 and 2040, respectively. In contrast, optimum scenario adheres to the 2030 and 2050 horizons with the most economical suitable combination. The proposed model analyses the short-term hourly dynamics typical of unit commitment problems. Furthermore, energy storage systems are sized by decoupling energy and power requirements, sector integration is applied as generic demand response and water desalination and transport have been considered.

The notable findings of this work are related to the price-based scenario ranking and their different configurations. The BAU scenario is not only the most expensive by far but also the one with the highest emissions, which double over the horizon. The policy-driven and optimal scenarios are 85% and 90% cheaper than BAU, approximately. Both scenarios consider the existing reverse osmosis desalination plants on the island and the recently initiated land transport electrification. The optimal scenario requires significantly less power capacity as it maintains a minimal level of fossil fuels while still achieving 96% renewable rates. In fact, the last two scenarios provide very similar configurations for the future, highlighting their adaptability to the country's evolution.

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