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Exploring Pathways to Increase Renewable Energy Penetration in Cabo Verde Islands

Presented the 18/09/2023 and by:

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ABSTRACT

Despite having a vast potential for renewable electricity production, Cabo Verde Islands have a low penetration rate of renewable energy, presenting a high reliance on imported fossil fuels. Like most Small Island Developing States (SIDS), Cabo Verde experiences some difficulties in the electricity sector mainly due to this high dependence on fossil fuels. As of 2021, the installed renewable energy capacity in the country was 35 MW, a value far below its estimated total potential of 2600 MW, and more than 80% of the country's electricity was produced from non-renewable sources. Increasing renewable energy penetration should be a priority to address the challenges faced by the country's energy sector and to address concerns related to sustainable development. This research uses an energy modelling tool (EnergyPLAN) to explore pathways to improve renewable energy penetration in four islands of the archipelago Cabo Verde, namely, Santo Antão, São Vicente, Sal, and Santiago. Two scenarios are crafted with the goal of attaining 50% and 100% renewable energy penetration in 2030 while considering the available renewable energy sources. Furthermore, for being an alternative scantily explored, a techno-economic analysis of the interconnection of the Santo Antão and São Vicente's power systems is performed. The results of the simulations and scenarios provide evidence of the technical feasibility of a 100% renewable energy-based energy system in the case study islands. Higher renewable penetration levels are achieved through direct electrification of in-land transport. Moreover, the results shed light on the impacts of interconnection between the islands to increase renewable energy penetration levels. Investing in renewable energy sources, especially in SIDS, deemed the most vulnerable to climate change, is related to environmental and economic concerns and strategic planning for the country's development. Therefore, transitioning to low-carbon energy alternatives such as electric vehicles powered by renewable energy should be prioritised in Cabo Verde's energy policies to ensure that the country reaches sustainable development.

Renewable energy sources integration, Islands energy planning, Interconnected power systems, Scenario analysis, Energy Transition

RÉSUMÉ

Malgré un vaste potentiel de production d'électricité renouvelable, les îles du Cabo Verde ont un faible taux de pénétration des énergies renouvelables, ce qui les rend très dépendantes des combustibles fossiles importés. Comme la plupart des petits États insulaires en développement (PEID), le Cabo Verde connaît des difficultés dans le secteur de l'électricité, principalement en raison de cette forte dépendance à l'égard des combustibles fossiles. En 2021, la capacité installée d'énergie renouvelable dans le pays était de 35 MW, une valeur bien inférieure à son potentiel total estimé à 2 600 MW, et plus de 80 % de l'électricité du pays était produite à partir de sources non renouvelables. L'augmentation de la pénétration des énergies renouvelables devrait être une priorité pour relever les défis auxquels est confronté le secteur énergétique du pays et pour répondre aux préoccupations liées au développement durable. Cette recherche utilise un outil de modélisation énergétique (EnergyPLAN) pour explorer les voies d'amélioration de la pénétration des énergies renouvelables dans quatre îles de l'archipel du Cabo Verde, à savoir Santo Antão, São Vicente, Sal et Santiago. Deux scénarios sont élaborés dans le but d'atteindre une pénétration de 50 % et de 100 % des énergies renouvelables en 2030, tout en tenant compte des sources d'énergie renouvelables disponibles. En outre, une analyse technico-économique de l'interconnexion des systèmes électriques de Santo Antão et de São Vicente est réalisée, car il s'agit d'une alternative peu explorée Les résultats des simulations et des scénarios démontrent la faisabilité technique d'un système énergétique basé à 100 % sur les énergies renouvelables dans les îles étudiées. Des niveaux plus élevés de pénétration des énergies renouvelables sont atteints grâce à l'électrification directe des transports terrestres. En outre, les résultats mettent en lumière l'impact de l'interconnexion entre les îles pour augmenter les niveaux de pénétration des énergies renouvelables. L'investissement dans les sources d'énergie renouvelables, en particulier dans les PEID, considérés comme les plus vulnérables au changement climatique, est lié à des préoccupations environnementales et économiques et à la planification stratégique du développement du pays. Par conséquent, la transition vers des alternatives énergétiques à faible teneur en carbone, telles que les véhicules électriques alimentés par des énergies renouvelables, devrait être une priorité dans les politiques énergétiques du Cap-Vert afin de garantir que le pays parvienne à un développement durable.

Intégration des sources d'énergie renouvelables, planification énergétique des îles, systèmes électriques interconnectés, analyse de scénarios, transition énergétique

ACRONYMS AND ABBREVIATIONS

AOSIS - Alliance of Small Island States

BAU - Business as Usual

BESS – Battery Energy System Solution

CEEP – Critical Excess of Electricity Production

COP21 - Conference of Parties of Paris

ECOWAS - Economic Community of West African States

ESS - Energy Storage Systems

EVs - Electric Vehicles

GDP - Gross Domestic Product

GHG - Greenhouse Gas

IPCC - Intergovernmental Panel on Climate Change

IRENA – International Renewable Energy Agency

MLR - Multivariate Linear Regression

MSW - Municipal Solid Waste

PPP - Public-Private Partnership

PSH - Pump Storage Hydro

PV - Photovoltaic

RE - Renewable Energy

RES - Renewable Energy Sources

SA - Santo Antao Island

SIDS - Small Islands Development States

SIDS -Small Islands Developing States

SL - Sal

ST - Santiago

SV - Sao Vicente

V2G - Vehicle-to-Grid

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1. INTRODUCTION

1.1. Context/background

Renewable Energy (RE) is gaining significant importance in island nations due to its potential to offer a range of benefits in terms of sustainable development. According to Meschede et al. (2022), more than 740 million people reside on islands, which are frequently viewed as regions with the best conditions for deploying 100% RE systems. This is mainly due to their abundant renewable energy sources (RES), small size (in most cases), and less complex energy systems, which make it easier to develop and implement energy strategies.

Several studies, including Harrison & Popke (2018) and Meschede et al. (2022), indicate that islands are frequently considered experimental laboratories for implementing RE strategy and promoting sustainable development; for Meschede et al. (2022), islands serve as models to demonstrate smart energy systems and sector coupling and to test higher levels of RE penetration, while Harrison & Popke (2018) suggest that occurrences in islands can provide insights and lessons applicable to mainland life.

The integration of RES on islands constitutes both opportunities and constraints (Alves et al., 2020). According to IRENA (2016), Small Islands Developing States (SIDS) have the potential to meet all their energy needs with a combination of RE technologies. SIDS can become more energy-independent by reducing their reliance on imported fossil fuels – a common trait on islands. Moreover, the risk of supply disruptions and price volatility associated with imported fossil fuels can be decreased by integrating RES, which can consequently increase energy security. On the other hand, islands' peculiar geographic features, such as remote location, limited land area and scarce resources, make energy planning of utmost importance. It is essential to carefully analyse islands' unique context and recommend local approaches for energy generation to meet their specific challenges and energy needs effectively.

1.2. Problem and Research Questions

Despite the considerable potential of RE and its associated advantages for energy planning, many islands, including the Cabo Verde Islands, still heavily rely on imported fossil fuels to meet their energy needs (Kuang et al., 2016). For instance, although the Cabo Verde islands have an identified RE potential of 2600 MW (Gesto Energia S.A., 2011b), only 35

MW is installed, and it contributes to the generation of 18.4% of the archipelago’s electricity (MICE, 2023).

Alarmingly, approximately 82% of Cabo Verde's total energy supply is derived from imported petroleum products (MICE, 2019), with the transport sector being the primary fossil fuel consumer.

The high reliance on fossil fuels leaves the archipelago vulnerable to external shocks. For example, the health and economy crisis triggered by the COVID-19 pandemic, associated with the geopolitical tension caused by Russia’s invasion of Ukraine in 2022, further exacerbated the socioeconomic vulnerabilities of main world markets and significantly impacted Cabo Verde’s economy. In 2020, Cabo Verde experienced a recession triggered by the economic impact of the pandemic. The recession led to a 14.8% decline in Gross Domestic Product (GDP), a surge in public debt reaching 156%, and an unemployment rate of 14.5%, as reported by the Central Bank of Cabo Verde (BCV, 2021).

Moreover, this dependence on imported fossil fuels has additional adverse consequences, including fuel price volatility and soaring electricity prices. Cabo Verde is known for having one of the highest electricity tariffs in West Africa (IRENA, 2016), with an average rate of 0.39 $/kWh in 2023 (ARME, 2022).

The increase in demand over the past decade, which is evident in a notable rise from 346 GWh in 2010 to 507 GWh in 2019 (Costa, 2014; MICE, 2023), coupled with the current intensification during peak demand periods, poses challenges to the country’s existent infrastructures and available resources. The national electricity and water company ELECTRA, SA. (2019) reported 235 blackouts during 2019, mostly occurring on small islands with the most unreliable grid (Coutinho et al., 2020).

Furthermore, islands are among the regions most affected by climate change, making energy planning an even more crucial endeavour. According to the Intergovernmental Panel on Climate Change (IPCC)’s report on Climate Change Impacts, Adaptation and Vulnerability, increased temperatures, tropical cyclones, storm surges, droughts, changes in precipitation patterns, sea level rise, coral bleaching and invasive species are among the many factors affecting small islands (Mycoo et al., 2022). Consequently, most island nations, including Cabo Verde islands, must commit to addressing climate change issues. In this sense, sustainable energy planning offers an excellent opportunity for SIDS, where energy security, environmental preservation, and economic development are closely intertwined, to tackle the challenges faced.

In this scenario, RE emerges as a critical element in Cabo Verde’s strategy to address the energy sector's problems, limiting the quest for sustainable development. RE can provide reliable, clean, and affordable energy while promoting sustainable development and guaranteeing the well-being of the citizens. The available RES, relatively small population and the country’s political will to transform its energy sector make Cabo Verde an ideal case to demonstrate RE's economic and technical viability.

Within this context, by examining the difficulties and opportunities associated with high integration of RE systems, this research aims to fill some of the literature gaps related to energy planning concerning the Cabo Verde Islands, with a specific focus on four islands of the archipelago, namely, Santo Antão, São Vicente, Sal, and Santiago. The existing body of literature considering Cabo Verde islands has only focused on a few isolated islands, namely Santiago and S. Vicente (Ferreira et al., 2020; Pombo et al., 2022; Segurado et al., 2011), presumably because their considerable energy needs, a more comprehensive analysis of a more extensive range of islands within the archipelago can provide a bigger picture of the country’s energy system. As an archipelago's islands are intrinsically interconnected, therefore, research must include comprehensive energy planning, considering the potential benefits and challenges in connecting and balancing RES in favour of the country.

Moreover, the existing literature primarily focuses on the power sector, disregarding other critical energy consumers, such as transportation. According to Gils & Simon (2017), most research on island-specific energy systems has mainly concentrated on the power sector, ignoring the potential advantages of sector coupling (Gils & Simon, 2017). In Cabo Verde, the transport sector is by far the largest consumer of fossil fuels (Costa, 2014; MICE, 2019), making it a crucial sector for the transition to sustainable energy.

Furthermore, considering the scant discussion around the interconnection of island power systems and the several benefits of this strategic approach, this research aims to analyse this possibility carefully. Specifically, it seeks to interconnect the Santo Antão and São Vicente Islands, aiming to assess the power system's interconnection potential benefits.

Considering the challenges faced by Cabo Verde's energy sector, this research seeks to address critical questions surrounding the sector and its transition towards a more sustainable energy supply. The research questions that direct this thesis are:

1) What are the main challenges faced by Cabo Verde's energy sector?
2) Which strategies and technological changes are required for Cabo Verde to transition to a 100% RE system?
3) If a 100% RE system is adopted by 2030, what would be the environmental and socioeconomic impact on the country?
4) If the islands' power systems are interconnected, to what extent would they increase their RES penetration, and is this interconnection more cost-effective than non-interconnected power systems?

1.3. Objectives

The overall objective of this study is to analyse the current situation of the country's energy sector to suggest later relevant energy strategies and alternatives for the near future that can successfully increase the penetration of RES in their energy systems while considering their socio-economic and environmental aspects. Special attention will be given to analysing the behaviour of the islands' power systems when an interconnection scenario is proposed to increase RE penetration.

To fulfil the above-mentioned overall objectives, the following specific objectives are proposed:

a) Identify Cabo Verde's energy sector's main challenges and opportunities.
b) Assess the RE policies and strategies already adopted in Cabo Verde.
c) Investigate and evaluate the strategies and technological changes required for Cabo Verde to transition to a 100% RE system.
d) Assess the environmental and socioeconomic impacts of a 100% RE system in Cabo Verde.
e) Compare the costs and benefits of interconnected power systems with decentralised power systems in Cabo Verde.

1.4. Thesis structure

This master thesis is divided into four chapters and additional sections of introduction, conclusions, references, and appendices. The first section is the introduction, and it presents the context in which the research is inserted, the problem and research questions, the objectives, and the structures of the work. Chapter 1 presents a literature review on the islands' energy planning, including a brief review of modelled cases for the Cabo Verde Islands. In Chapter 2 an overview of Cabo Verde Island's energy context is provided. The Chapter provides a description of the country's energy sector by presenting in detail the current energy sector situation, energy policies/targets towards RE and the main challenges and opportunities faced by the energy sector. Subsequently, in Chapter 3, the description of the methodology proposed for this research is presented. Data collection procedures and scenario development steps are explained in detail in Chapter 4. Chapter 5 encompasses the results and discussion. Conclusion, bibliographic references, and appendices can be found in section 6, 7 and, respectively.

2. LITERATURE REVIEW

This chapter provides a literature review on island energy planning to examine this growing research field. The chapter briefly overviews this research field's significance, explores successful case studies, and demonstrates the island’s unique challenges and opportunities. Additionally, the chapter provides an overview of the modelled cases specific to Cabo Verde that aimed for 100% RE integration.

2.1. Energy Planning for Islands

Several papers have addressed the role of RE integration on islands’ energy systems. SIDS face amplified challenges due to their unique features concerning GHG emissions and fossil fuel depletion. In their study, Barney et al. (2021) propose coupling RES with energy storage, such as batteries, to offer a cost-effective and sustainable way to reduce fossil fuel use and its environmental effects. Moreover, small islands heavily dependent on fossil fuel imports can increase their self-reliance by employing their endogenous resources. Alves et al. (2019) suggest that despite the higher initial costs, RE investments are becoming competitive due to expensive fuel imports, promoting economic resilience and environmental sustainability.

In this context, it is notable that SIDS have established some of the world's most ambitious RE targets (Dornan & Shah, 2016). Additionally, SIDS, represented by the Alliance of Small Island States (AOSIS), has been reported as the foremost champion of enhanced climate ambition consistent with the 1.5°C temperature goal set in the Paris Agreement (IPCC, 2018). This underscores their dedication to fighting climate change and the essential role RE integration plays in achieving these goals.

Likewise, the increasing importance of islands in the context of regions with 100% RE systems in the last ten years, as inferred by Meschede et al. (2022), can be interpreted as part of a broader trend of using islands as blueprints for innovative RE strategies and projects. This trend is exemplified by the Caribbean region, which has been the focus of a study conducted by Harrison & Popke (2018), highlighting the region's role as a laboratory for reshaping legal and regulatory environments, reengineering energy infrastructures and landscapes, and testing new RE policies and projects. Meanwhile, Mimica & Krajačić (2021) emphasised the increasing importance of islands' energy planning, mainly due to the European Union's keen efforts to fight climate change. The authors suggest that islands may act as "living labs" for cutting-edge initiatives and technology, highlighting their critical importance in the shift to a clean and sustainable energy environment (Mimica & Krajačić, 2021, p. 1).

Many islands and archipelagos have significantly progressed or achieved 100% RE integration. Tokelau, a territory of New Zealand, provided for over 95% of the nation's electricity generation needs through the installation of a 1 MW solar power plant (Ellsmoor, 2016), as well as the island of El Hierro in the Canary Islands, which achieved 100% RE through a combination of wind and hydroelectric power (Godina et al., 2015).

Several researchers have directed their focus towards energy planning for islands. Gils & Simon (2017) presented a novel approach in their study. The authors introduced an innovative methodology for energy scenario development aimed at achieving a 100% RE supply in the Canary Islands. They combined Mesap-PlaNet, a long-term energy system balancing tool, with REMix, a deterministic high-resolution energy system optimisation model, to simulate pathways towards an entire RE supply. Their model encompassed high temporal and spatial resolution with an accounting framework. The possibility of interconnecting the Canary Islands was also considered, leading to significant findings. The authors found that by interconnecting the islands' power system, the overall size of the power plant park is reduced, and its composition is changed. Overall, the paper provides helpful insights regarding the potential benefits offered by sector coupling and energy exchange between neighbouring islands.

Considering Cabo Verde's case, it was found that several studies focused on analysing its energy system (Nordman et al., 2019; Segurado et al., 2011; Tavares et al., 2019). However, from the author's knowledge only (Ferreira et al., 2020; Pombo et al., 2022) were found to be solely concentrated on 100% RE planning considering the power sector. Notably, these studies focus on the islands of São Vicente and Santiago, presumably because of their high significance for Cabo Verde's energy system. Despite using different methodologies and strategies, their common goal was to increase the integration of RES inside Cabo Verde's energy system. Moreover, Nordman et al. (2018) discussed the possibility of achieving a 100% RE goal in the country while addressing the challenges related to the possible adaptation of a 100% RES system.

Pombo et al. (2022) focused on the São Vicente island's energy transition roadmap. The authors' ambitious objective of total reliance on RES is explored and evaluated using the

Generation and Storage Expansion Planning (GSEP) method and considering technologies that align with the country's strategies regarding RES integration. In their analysis, three scenarios were considered, namely, BAU, Optimal and Green, considering a planning period of 20 years. The study's main results shed light on the costs and quantitative differences between the scenarios. The scenario considering 100% RE penetration in 2040 is the most expensive, primarily due to the over-installation of renewable capacities due to the high seasonality of the available RES and costs associated with energy storage systems (ESS).

Similarly, Ferreira et al. (2020) developed a comprehensive plan for transitioning Santiago Island to a 100% RE system. The approach is also based on a Generation Expansion Planning (GEP) method used in previous literature and adopted to Santiago Island. The researchers used a programming language - General Algebraic Modelling System (GAMS) - to define the planning model and obtain the results. Ferreira et al. (2020) findings are significant because they show the possibility of implementing a scenario with 100% RE in Santiago while adopting current in-use technologies. However, their research highlights the difficulties and restrictions that should not be understated. The authors suggested that the energy shift is technically feasible but faces significant obstacles due to economic factors, including high investment costs and infrastructure constraints. Their results demonstrate the theoretical viability of a high RE system. However, they also show high costs and variability of these technologies, which may result in unaffordable expenditures, especially considering that Cabo Verde is one of the world's poorest and smallest developing islands (Ferreira et al., 2020). The authors recommend improvements that should be considered in future studies, including incorporating energy storage solutions and adopting an hourly approach to better address seasonality and day-night variability.

The two publications provide essential insights into the Cabo Verde Islands' energy planning. Nevertheless, both considered only the power sector, leaving essential sectors such as the transport sector out of their models. On the other hand, Nordman et al. (2018) is one of the few papers that address energy planning for all the archipelago's islands. However, their approach is rather qualitative. Publicly available information was the primary source used in their research. A comprehensive review of peer-reviewed literature was conducted, and industries and other organisations provided technical reports for their research. As a further part of their methodology, they engaged in meaningful discussions with energy experts within the country. Nordman et al. (2019) suggest that the goal to achieve a 100% RE system in Cabo Verde should be adapted to each island, considering individualised strategies. They concluded that while technically feasible, achieving a 100% RES system by 2025 is unlikely due to the time required for assessments, regulatory compliance, financing, and other project development aspects.

The findings and strategies adopted in these papers provide valuable information regarding energy planning for the islands in the study. The revealed technical and economic challenges associated with a 100% RE system and the emphasised significance of the island-specific approach will significantly contribute to this research discussion.

A review of 100% RE scenarios on islands was done by Meschede et al. (2022), which provided a comprehensive and holistic view of island energy system studies, focusing on achieving 100% RE penetration. From their analyses, 100% of RES systems on islands are technically feasible and economically viable by implementing adequate solutions according to the island's reality and available resources.

The author's contribution to the literature highlights significant gaps in planning for 100% RE systems. They draw attention to the need for more sector coupling assessments, which prevents a thorough grasp of problems and opportunities. According to Meschede et al. (2022), energy planning should consider all sectors of the energy system. However, there is still a strong emphasis on the power sector. Opinion also shared by Hansen et al. (2019), which discussed the lack of a uniform definition for 100% RE systems planning. According to the latest, some studies only consider the electricity sector, while others also consider the heating/cooling, transportation, and industrial sectors (Hansen et al., 2019).

In the existing literature, discussions regarding interconnections between the mainland and neighbouring regions have been relatively sparse, with few concrete cases providing illustrative examples of this possibility. Notably, Europe stands out as the region with the most tangible instances of island interconnection with the mainland, exemplified by cases such as Aland (Child et al., 2017) and the Greek islands (Georgiou et al., 2011). However, the implementation of such interconnections has been hindered by the considerable cost associated with submarine transmission lines, as highlighted by Kuang et al. (2016). Consequently, the absence of grid connections between islands and the mainland and adjacent islands remains a prevalent issue.

The advantages of island interconnection have been studied by Alves et al. (2019) and Georgiou et al. (2011). According to Georgiou et al. (2011), connecting islands with the mainland offers promising economic and environmental benefits, promoting the expansion of the power sector sustainably and permitting the development of high-potential RES. The interconnection of the electrical grid on islands like Pico and Faial (Azores archipelago), according to Alves et al. (2019), results in a noticeably higher proportion of RES penetration as compared to Business-as-Usual (BAU) scenarios. These results highlight the potential of island interconnection in promoting the use of RE and increasing the sector's overall sustainability objectives. Considering the many advantages of interconnecting islands' power grids, future studies must identify pathways toward the progressive transition to fully RE from the existing conventional power grid.

Switching to 100% RE systems on islands presents several difficulties and obstacles (Atteridge & Savvidou, 2019). For implementation to be successful, technical, financial, regulatory, and societal challenges must be addressed. They are recognised for facing various difficulties, including unreliable electrical grid connections and high fuel costs (Mimica & Krajačić, 2021). The increased fuel cost is due to high dependence on imported fossil fuel, leading to supply disruption and price volatility risks. Additionally, the intermittent nature of RES, such as wind and solar, constitutes one of the main challenges regarding integrating high shares of RE energy, implying the need for a storage solution to address this issue. This can aggravate grid stability problems and a mismatch between demand and supply (Alves et al., 2020). Furthermore, islands present unique geographic challenges, such as limited land area and resources, remote location, and vulnerability to natural disasters, constraining the system planning and the transition to a more sustainable energy system.

Islands also possess distinctive qualities. They have specific advantages, such as a better understanding of energy requirements and resource availability. Introducing new technology to islands offers a chance to create scalable, reproducible solutions that can be applied to mainland locations (Mimica & Krajačić, 2021). As mentioned in the introduction chapter, they are often considered blueprints for sustainable energy system transition. Child et al. (2017) pointed out why islands constitute exciting cases for energy planning. The authors indicated their geography, energy system complexity and regulatory framework (which is usually less complex than continental systems) and the fact that islands are typically associated with significant imports of expensive fossil fuels from or power interconnections with mainland energy suppliers as primary reasons for choosing islands as case studies.

2.2. Review of Modelled Cases Using EnergyPLAN

In this research, EnergyPLAN was selected as a research tool. The operation mode and principles behind it are explained in detail in Chapter 4. Here, a short review of a few peer-reviewed papers using EnergyPLAN as a research tool aims to delve into the outcomes and findings generated by these studies. The insights obtained from this thorough analysis provide valuable information and a deeper understanding of the model's effectiveness regarding energy planning. Furthermore, these insights are used to engage in discussions concerning the results.

With a particular emphasis on smart energy systems, EnergyPLAN has been utilised as a research tool to build future sustainable energy solutions (Lund et al., 2021). For instance, Child et al. (2017) used EnergyPLAN to construct scenarios for Aland Islands' future energy system based on various combinations of domestic wind and solar photovoltaic power production, expanded domestic energy storage solutions, electrified transport, and strategic energy carrier trade. The authors found out that for the case of Aland Island, it is possible to achieve a 100% RE-based domestic energy generation by 2030 with or without resorting to imported energy carriers, such as sustainable biofuels or electricity. Child et al. (2017) is one of the few papers considering the socioeconomic implications of high integration of RES in energy systems. Based on the International Renewable Energy Agency (IRENA) estimations, the authors calculated the total number of jobs per year for each one of their scenarios. SDF Syn, a scenario considering high synthetic fuel production, had the highest job creation. Interestingly, they found that scenarios with higher annualised costs tended to result in more job opportunities, indicating a potential socioeconomic benefit in exchange for high investments. On the other hand, the least-cost scenarios showed fewer job creation opportunities.

Connolly et al. (2011) used EnergyPLAN to design three scenarios to examine the technical implications of a 100% renewable energy system for Ireland. According to the authors, the best way to convert Ireland to a 100% renewable energy system is through sector coupling, i.e., to implement district heating, heat pumps, and a transportation mix of electricity, hydrogen, and biomass (Connolly et al., 2011).

The interconnection between the island Faial and Pico was first proposed by Alves et al. (2019). The objective was to assess the techno-economic and environmental implications of the proposed scenario. Further, the authors evaluated the impact of this interconnection on the path towards a 100% RES system (Alves et al., 2020). In both cases, EnergyPLAN was employed as a research tool to simulate scenarios allowing interconnection between the two islands. The interconnection of Faial and Pico led to significant gains in the energy system. For the first case, results showed that when considering the interconnection of Pico's and Faial's power systems, the RES penetration share increases up to 65.6%, a share 50 percentage points (pp) superior to the 2030 BAU scenario (Alves et al., 2019). In their second work, Alves et al. (2020) proposed three scenarios, namely BAU, Interconnect, and not-interconnected, to achieve a 100% RES energy system in the Pico and Faial Islands. The interconnected scenarios considered three transition years (2030, 2040 and 2050) with different specifications, considering the power and transport sector. Results show that to achieve a 100% RES system in Pico and Faial Islands, it is necessary to considerably oversize the power generation system, resulting in increased costs for the produced energy (Alves et al., 2020).

Child et al. (2018) employed EnergyPLAN to simulate 100% RE scenarios with a highly participatory V2G system in the Aland Islands (Child et al., 2018). The authors found that the scenario with high participation in V2G resulted in less gas storage, electrolyser capacity, methanation capacity, and offshore wind power capacity than other scenarios with lower V2G participation. The authors noted that V2G serves as storage for future use and acts as a buffer, helping bridge the gap between intermittent renewable energy generation and consumption (Child et al., 2018).

Similarly, it has been employed to explore alternative transport pathways to decarbonise Nicaragua’s transport sector (Cantarero, 2019). The author provided a set of transport pathways required for Nicaragua to transit to a fully decarbonised system, which can also be applied to other small economies dependent on fossil fuels. Results show that compared with conventional internal combustion engine vehicles, EVs provide their owners with fuel savings, which makes them an economically appealing alternative. Additionally, a social analysis regarding implementing a mass transportation system was conducted. According to Cantarero (2019), a mass transport system in the capital city of Nicaragua will not only improve the quality of transport mode but also bring benefits to the community, such as better communication and integration in the city and job opportunities. Overall, the results from this study indicate that transport planning and increased investment in public transport infrastructure are crucial for decarbonisation.

3. CABO VERDE ISLANDS ENERGY CONTEXT

3.1. Country's Profile

Cabo Verde is an African island country, a member of SIDS and AOSIS. It is located about 500 km off the West Coast of Africa and is a member state of the Economic Community of West African States (ECOWAS).

The country is composed of ten small islands (Figure 1), nine of which are inhabited. The islands are aggregated into two categories: Barlavento and Sotavento. The islands of Santo Antão, São Vicente, Santa Luzia, São Nicolau, Sal, and Boavista are in the North-Barlavento Group, which means "where the wind blows from" and the islands of Maio, Santiago, Fogo, and Brava are in the South - Sotavento Group, meaning "where the wind goes". The islands are separated by considerable distances, ranging from 10 km to more than 100 km, Santa Luzia and São Vicente being the closest to each other, followed by S. Vicente and S. Antao.

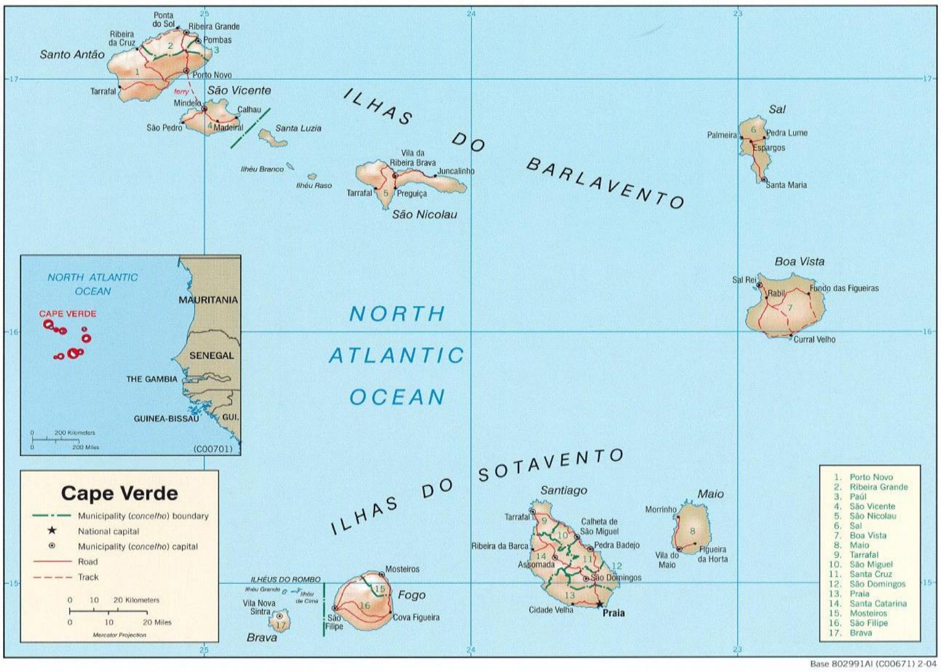

Figure 1 Topographic map of Cabo Verde

Source: Retrieved from Cape Verde, accessed on 26/05/2023.

The topography of the archipelago is rugged except for the islands of Boavista, Sal, and Maio. On the other islands, it is possible to find altitudes exceeding 1,000 meters; the highest point in the country is 2,882 meters on Fogo Island ("Pico do Fogo" - an active volcano). Table 1 presents some demographic and geographic information about each one of the Cape Verde islands.

Table 1 Geographical and demographic features of Cabo Verde islands

Islands Name	Superficies (km^2)[a]	Max. Altitude (m)[a]	Population (2021)[b]
Santo Antão	779	1,979	36 950
São Vicente	227	725	75 845
Santa Luzia	35	395	-
São Nicolau	343	1 304	12 306
Sal	216	406	33 615
Boa Vista	620	387	12 798
Maio	269	436	6 330
Santiago	991	1 392	273 988
Fogo	476	2 829	33 754
Brava	64	976	5 647

Sources: [a]Duarte & Romeiras (2009, p. 501). [b]INE (2022)

The capital of Cabo Verde is Praia, located on the largest island, Santiago. Santiago is home to more than half (55.7%) of Cabo Verde's total population. The majority of the population (74,1%) resides in urban areas (364,106 inhabitants), and more than one quarter (26.9%) is concentrated in the capital city Praia (145,378 inhabitants) (INE, 2022).

The closest country to the Cabo Verde Islands is Senegal. Therefore, it belongs to the Sahelian countries with arid, semi-arid, hot, and dry climates, and it is also affected by scarce rainfall. According to the World Bank Group (2018), Cabo Verde is the second African country with the lowest freshwater availability per capita, and only 10% of its land is considered arable.

Three seasons can be identified in Cabo Verde Islands: a rainy season from July to October, a transition season from November to February and a transition season from March to June (World Bank Group, 2021). The annual average temperature in the country rarely rises above 25ºC and never falls below 20ºC thanks to the moderating action that the ocean and the trade winds exert on the temperature (GCV, 2023).

The country has very limited natural resources. Only five islands (Santo Antão, S. Nicolau, Santiago, Fogo, and Brava) can develop small-scale agricultural production, and most of the country's water for consumption is desalinated due to poor rainfall and limited fresh water.

3.2. The Energy Sector

Energy supply in countries with a fragile economy, such as Cabo Verde, exerts considerable pressure on economic stability. Therefore, the energy sector is a crucial and critical strategic component for the country’s sustainable development.

Cabo Verde's energy sector faces challenges due to its insularity and high dependence on imported petroleum products. As an archipelago, each island possesses its energy system, with Santiago, S. Vicente, and Sal having the highest energy needs. Over the past decades, these three islands accounted for almost 90% of the total electricity generated in the country (Gesto Energia S.A., 2011b), as depicted in Figure 2.

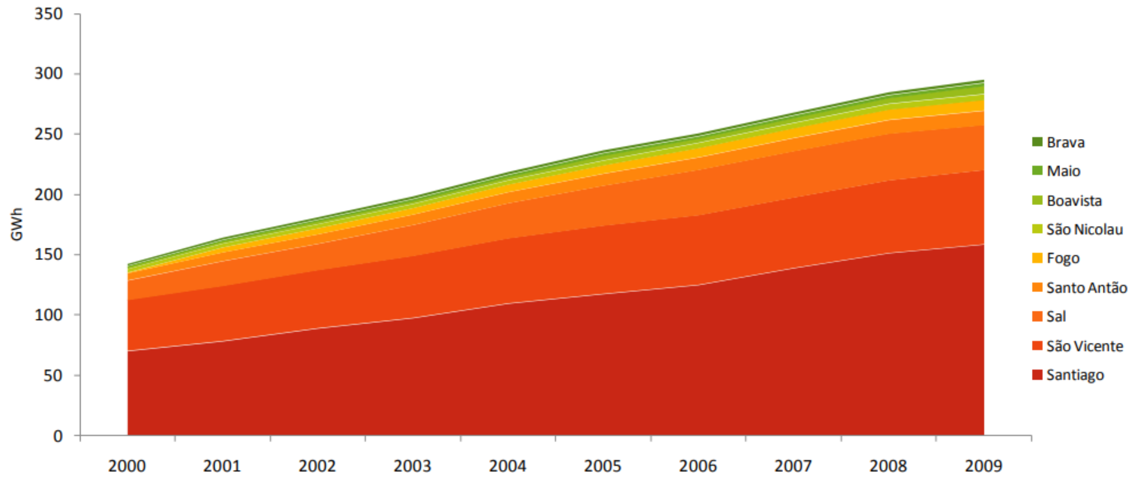

Figure 2 Historical evolution of electricity Consumption in Cabo Verde Islands
Source: Gesto Energia S.A. (2021b)

The country’s energy mix primarily relies on imported petroleum products, firewood, wind energy, and a small contribution from solar power (MICE, 2019), as seen in Figure 3. Firewood is predominantly utilised in rural areas for cooking; however, it poses environmental implications, considering the islands’ limited vegetation and wood resources.

The fuel distribution and storage process in Cabo Verde is explained by (Costa, 2014). The islands of S. Vicente, Sal, and Santiago act as the primary storage hubs, initially housing all imported fuels and then distributing the fuel to the remaining islands via marine transportation.

Transport, residential, and industrial sectors consume most of Cabo Verde's energy. The transport sector stands out as the largest consumer, accounting for 44% of the country's total energy consumption, whereas approximately 65% corresponds to terrestrial transportation (MICE, 2019). This demonstrates the significant role of road transportation in ensuring the mobility needs of the population.

Despite being a service-oriented country emphasising the tourism sector, the commercial and public services sectors contribute relatively less to the overall energy consumption, representing only 5% of the total energy usage. The distribution of energy use across various sectors and types is shown in Figure 4.

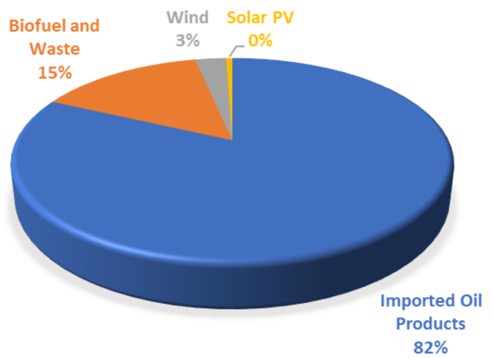

Figure 4 Cabo Verde's primary energy supply

Source: Based on data from MICE (2019)

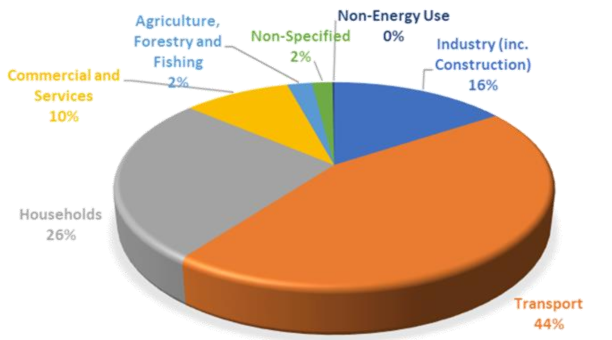

Figure 3 Total final energy consumption by sector

Source: Based on data from MICE (2019)

As mentioned, each island generates its electricity primarily from thermal power stations using diesel and fuel oil. Some islands ' Independent wind and solar energy producers feed the grid with RE.

In most urban areas, desalinated water is the only option, requiring a significant amount of electricity. For instance, in 2019, 6.8% of the total electricity produced was used in desalination, and 0.8% was used for water pumping (ELECTRA, SA., 2021).

The distribution of electricity in the Cabo Verde Islands poses a significant challenge within the energy sector, particularly concerning the power district. The electricity sector confronts an intricate problem due to substantial technical and non-technical losses. Data from 2019 show that the cumulative global power losses, including technical and non-technical losses, totalled about 110 GWh, or 24.8% of the total electricity generation (ELECTRA, SA., 2021). It is important to pay attention to Santiago Island, which showed the highest loss levels among the islands. Amounting to 87 GWh in losses in 2019, this island alone was responsible for losses equivalent to 35.6% of its production (ELECTRA, SA., 2021), highlighting the need for focused attention to address these losses adequately.

3.3. Renewable Energy Potential

As demonstrated in Figure 5, the islands of Cabo Verde have an estimated RE potential of 2,600 MW, having been identified more than 650 MW in concrete projects, with production costs lower than those of fossil fuels (Gesto Energia S.A., 2011b). Presently, the country's total installed RE capacity stands at 35 MW, with onshore wind farms accounting for 25.5 MW and the remaining capacity provided by Solar Photovoltaic (PV) farms.

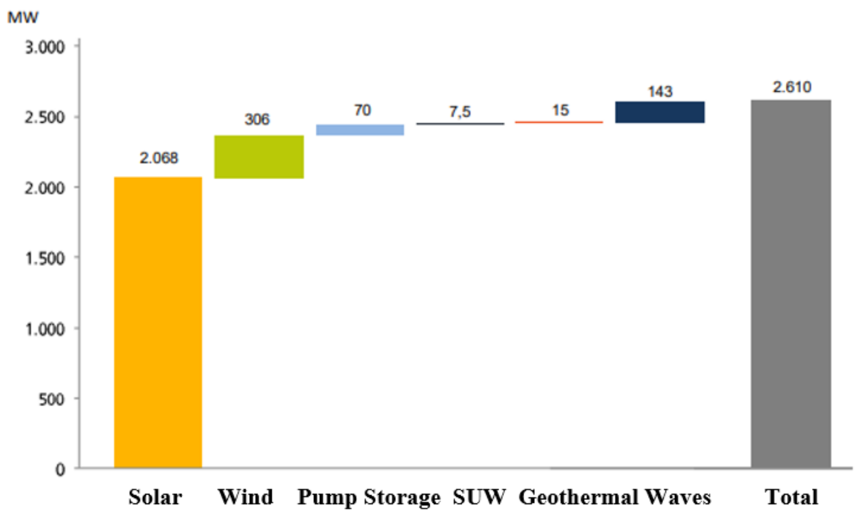

Figure 5 Identification of RE project per technologies

Source: Retrieved from Gesto Energia S.A. (2021)

3.3.1. Wind

Cabo Verde Islands' clean energy sources are dominated by wind. The initiatives for introducing RES in Cabo Verde's energy mix started in 2009 with Cabeólica, a Public Private Partnership (PPP) between a private company - Infraco Limited, and the Government of Cabo Verde. This agreement encompassed the development, financing, construction, ownership, and operation of four wind farms, collectively delivering a total installed capacity of 25.5 MW. These wind farms were strategically distributed across the islands of Santiago (9.35 MW), São Vicente (5.95 MW), Sal (7.65 MW), and Boa Vista (2.55 MW) (Cabeólica, S.A., 2022). Notably, these wind farms represented the pioneering commercial-scale projects within the ECOWAS region, positioning Cabo Verde as a regional leader in wind initiatives in that period (REN21, 2014).

According to the RE plan for Cabo Verde (*Plano Energético Renovável Cabo Verde)* (Gesto Energia S.A., 2011b), in terms of seasonality, there is an annual asymmetry in wind speeds, with two distinct periods:

- From January to June, there are high average wind speeds.
- From July to December, there is a significant decrease in wind speeds.

This seasonal pattern highlights the variation in wind conditions throughout the year in Cabo Verde. In Figure 6, it is possible to observe the mean wind speed surrounding each island. São Vicente has the highest wind potential, with an average wind speed ranging from 6 m/s to over 9 m/s (Gesto Energia S.A., 2011b). The other islands have varying degrees of potential, with Santo Antão having the lowest potential.

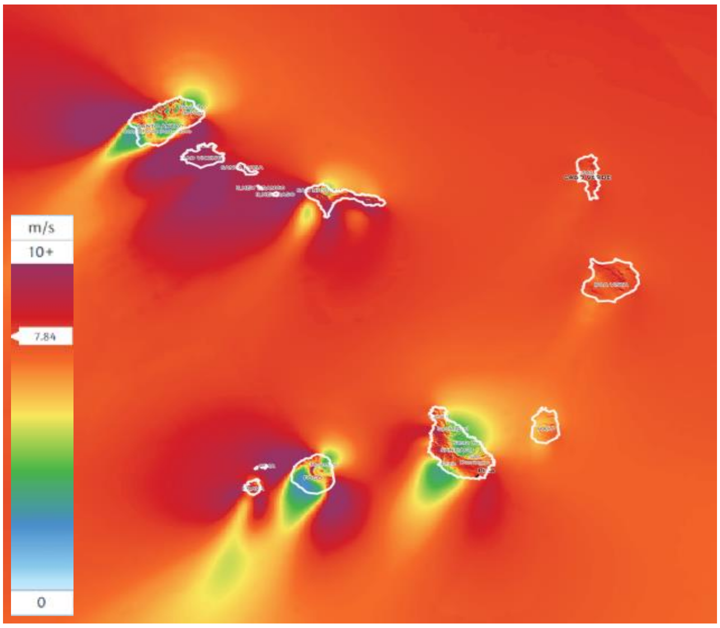

Figure 6 Mean wind speed at 100m

Source: Available at Global Wind Atlas accessed in 06/08/2023

3.3.2. Solar

Solar energy is the most abundant natural resource in Cabo Verde. The solar resource potential of Cape Verde can be observed in the map of global radiation (Figure 7). Gesto Energia S.A. (2011) described an average annual global radiation between 1,800 and 2,000 kWh/m2/year for most of the territory. The best regions identified in the report possess an average global radiation level ranging between 2,070 kWh/m2/year and 2,175 kWh/m2/year, with an estimated potential of 2,600 MW of solar energy producing about 4.7 GWh/year (Gesto Energia S.A., 2011b).

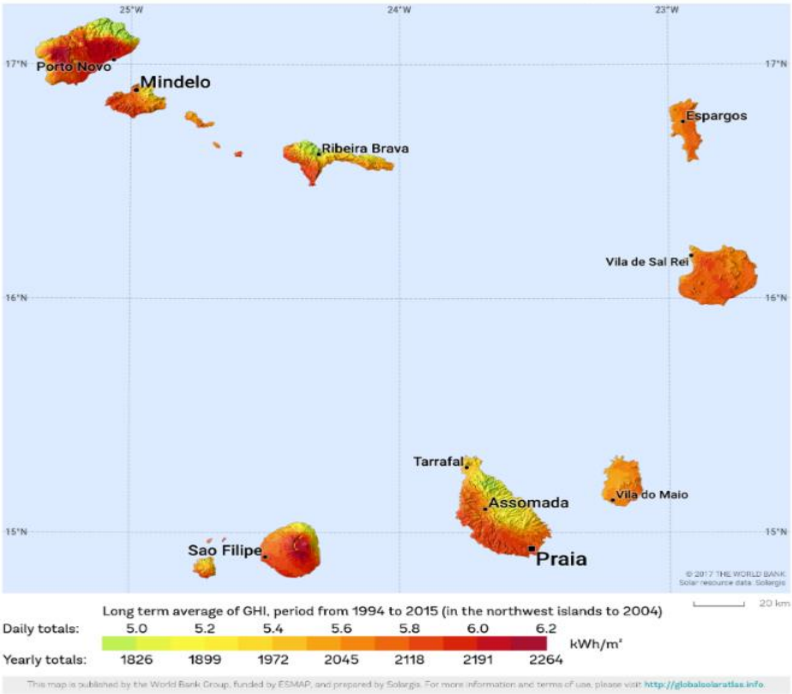

Figure 7 Global solar irradiation map

Source: Available at Global Solar Atlas accessed in 06/08/2023

3.3.3. Biomass and Hydro

Cabo Verde has an arid climate characterised by a history of droughts and torrential rainfall, which means that the annual precipitation is reduced, occurring in a concentrated manner in short periods. Therefore, it has limited water resources. Additionally, the country has limited vegetation. Thus, the use of biomass resources is constrained.

The islands of São Vicente, Sal, Boavista, Maio, and Brava do not have the potential for hydroelectric energy production due to factors such as reduced average annual runoff, small hydrographic basins, and limited level differences relative to sea level (Gesto Energia S.A., 2011b).

Santiago, Santo Antão, Fogo and São Nicolau have some potential to produce low-power hydroelectric energy, particularly on the island of Fogo, as it is the one with the areas with the highest values of average annual runoff and the most remarkable differences in level compared to sea water level. Nonetheless, due to the lack of detailed studies on the feasibility of harnessing hydroelectric energy, Gesto Energia S.A. (2011) concluded that the water resource has low potential and should not be a significant source for supplying the archipelago).

3.3.4. Municipal Solid Waste (MSW)

Regarding MSW, only the islands of Santiago and S. Vicente produce enough waste for energy transformation, especially in the main urban areas, such as Praia and Mindelo. The population of Praia and São Vicente corresponds to 26.6% and 15.4% of the total population of the archipelago, respectively, and is estimated to grow by 2.4% in the future due to the increase in urban populations (INE, 2022a). Therefore, MSW is expected to play a significant role in these islands' future energy mix. Gesto Energia S.A. (2011) identified potential for 5 MW and 2.5 MW power plants in Praia (Santiago) and Mindelo (S. Vicente), respectively.

3.3.5. Geothermal

Cabo Verde islands are volcanic; therefore, they satisfy all requirements for necessary geothermal resources, particularly Santo Antao and Fogo islands, which have seen recent volcanism and higher rainfall. Gesto Energia S.A. (2011) identified a potential of 3 MW on the Fogo Islands. However, studies need to be conducted to validate it. Therefore, the geothermal resource is considered uncertain.

3.3.6. Wave

Bernardino et al. (2017) show that the Cabo Verde Islands' coastline environment, particularly in some specific regions, presents significant wave energy resources that should be considered for extraction shortly. The mean wave power can be visualised in Figure 8.

The waves in the archipelago are affected by the trade of wind, especially in cooler periods when the wind potential is higher. On windward islands (S. Antão, S. Vicente, S. Nicolau, Sal, Boavista), the average energy flux is around 19 kW/m, while on leeward islands (Maio, Santiago, Fogo, Brava), it is closer to 15 kW/m. The resource is also seasonal, concentrated in just four months (December to March). Only four islands (Santo Antao, S. Vicente, Sal, and Boavista) show potential for pilot project development (Gesto Energia S.A., 2011b).

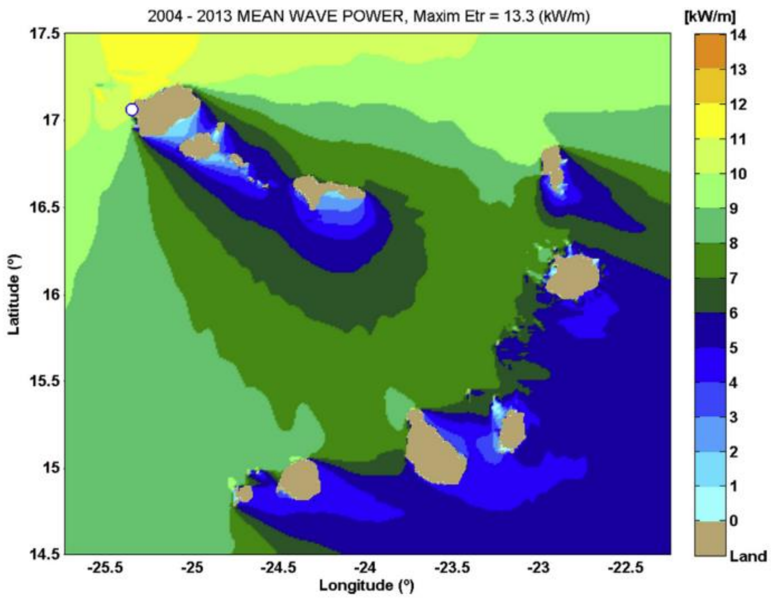

Figure 8 Mean wave power

Source: Retrieved from Bernardino et al. (2017)

The RE potential in Cabo Verde Islands is evident and has been comprehensively assessed through studies, exemplified by the work conducted by Gesto Energia S.A., 2011). Exploring these resources offers Cabo Verde the chance to successfully address the issues related to its current energy mix, primarily dependent on fossil fuels. This can bring benefits such as improving energy security, reducing GHG emissions, and promoting sustainable development in line with international environmental goals. Table 2 provides a synthesis of current installed capacities and identified potential projects to be explored in the archipelago.

Table 2 Current installed capacity and identified capacity to be explored

Islands	Installed Capacity [MW][a]			Identified projects for RE in CV [MW][b]					
	Thermal	Wind	Solar	Wind	Solar	Pumped-Storage	MSW	Geothermal	Wave
Santo Antão	6.6	0.5	0.08	35	176.5	-	-	-	3.5
São Vicente	20	6.85	-	20.5	62	10	3	-	3.5
São Nicolau	3.5	-	-	15.82	-	-	-	-	-
Sal	21.56	7.65	3.74	38.4	762.5	-	-	-	3.5
Boa Vista	18.76	2.55	-	20.4	-	-	-	-	3.5
Maio	1.55	-	-	14.5	-	-	-	-	-
Santiago	63.47	9.35	4.25	74.1	711.5	60	5	-	-

Fogo	5.124	-	-	19.6	928.5	-	-	3	-
Brava	1.38	-	-	6	-	-	-	-	-
TOTAL	**141.95**	**26.9**	**8.07**	**244.8**	**2641**	**70**	**8**	**3**	**14**

Sources: a) ELECTRA, SA. (2019); b) Gesto Energia S.A. (2011)

3.4. Main Energy Policies and Targets

Islands are among the regions most affected by climate change. According to the Intergovernmental Panel on Climate Change (IPCC) report on Climate Change Impacts, Adaptation and Vulnerability (Mycoo et al., 2022), increased temperatures, tropical cyclones, storm surges, droughts, changes in precipitation patterns, sea level rise, coral bleaching and invasive species are among the many things affecting small islands. In light of this, most island nations are compelled to commit to addressing climate change issues despite being the lower emitters. In the special report on Global Warming of 1.5°C (IPCC, 2018), the IPCC reported that the AOSIS has been the foremost champion of enhanced climate ambition consistent with the 1.5°C temperature goal set in the Paris Agreement. Many SIDS are adopting ambitious RE goals, not only to tackle climate change but also because of infrastructure planning or improvements.

The political parties overruling Cabo Verde Islands in the last 20 years have recognised the need to transition towards a more sustainable and diversified energy mix. As a result, the local government set ambitious RE targets and policies to encourage private investors to promote the development of RE in the country.

The Electricity Sector Master Plan (*Plano Director do Sector Electrico 2018–2040*) outlines Cabo Verde's goals to reach 30% of electricity from RES by 2025 and overpass 50% by 2030, as required by the Conference of Parties of Paris (COP21) (Resolução no 39/2019, 2019). The government's proposal prioritises investments in wind and solar energy deployment across the archipelago while encouraging energy efficiency measures.

Moreover, the government also has set ambitious goals for the transport sector. In 2019, a decree-law (Resolução nº 13/2019, 2019) entitled "*Carta Politica de Mobilidade Electrica"* (Electric Mobility Policy Letter) was published. The document contains the strategic vision of the country regarding electric mobility. It demonstrates the primary government's strategies to guide the creation of necessary conditions for electric mobility in the country.

The document also contains medium-term and long-term goals for integrating EVs in the country. The medium-term goals, to be achieved by 2025, include gradually implementing and having operational EV charging infrastructure in the main urban centres of Cabo Verde, establishing rules for new vehicle acquisitions by the Public Administration to be 100% EVs, and having at least 50% of EVs in new acquisitions for Urban Collective Transportation.

The long-term goals to be achieved by 2035 include having fully operational EV charging infrastructure throughout the national territory and adopting technological solutions to support the grid and market that enable the V2G system. Additionally, by 2035, the government set the objective of prohibiting the importation of vehicles equipped with internal combustion engines that use fossil fuels (gasoline or diesel).

These goals demonstrate Cabo Verde's commitment to transitioning to a more sustainable transportation system, encouraging EV adoption, and supporting the necessary infrastructure and regulations for their widespread use.

3.5. Challenges and Opportunities

When it comes to energy planning, islands have specific opportunities as well as challenges. On one hand, islands are susceptible to supply chain disruptions and usually have limited conventional energy sources. On the other hand, most of the time, they possess abundant RES that can be used to reduce their reliance on imported fossil fuels (Atteridge & Savvidou, 2019; Islam & Mamun, 2016). For small island communities with few resources, installing RES can be expensive and needs substantial infrastructure investments (Islam & Mamun, 2016). Participatory methods that involve local stakeholders can be utilised to improve the outcomes of energy plans and projects to address these issues and seize opportunities (Del-Busto et al., 2022).

In the specific context of Cabo Verde, the challenges stem primarily from two factors: the country's expansion and accelerated economic growth, accompanied by surging demand from both national residents and tourists (MECC, 2008). The energy sector faces several challenges, including limited planning and investment, fuel distribution issues between islands, insufficient storage and logistics, inefficient electricity production and distribution systems, low penetration of RES, the fragile nature of biomass resources, and a mounting water shortage.

Despite the challenges faced, the country offers promising opportunities to deploy RE. Its advantageous geographic location, close to 3 continents, associated with its strong political stability and human resources, provides a chance to strengthen the insufficient institutional capacity within the energy sector. Moreover, these points can serve as attractiveness for business opportunities to potential private investors interested in RE project deployment.

4. TOOLS AND METHODOLOGY

A combination of literature, desk research, interviews, and simulation using an energy planning modelling tool (discussed in subchapter 4.1) defines the research methodology of this master's thesis. The objective is to investigate ways to incorporate more RE into Cabo Verde islands' energy mix. This is accomplished by modelling different scenarios to explore potential paths for increasing RE integration by 2030, with 2019 as the base year.

The chapter's approach evaluates economic, environmental, and technological aspects to present reliable results. The guiding principles for shaping these scenarios stem from notions of self-reliance, effective use of RE, and the push for sustainability.

4.1. Energy System Modelling – EnergyPLAN

EnergyPLAN is an "Advanced energy system analysis computer model" created by the Sustainable Energy Planning Research Group at Aalborg University. It simulates the hourly operation of a national energy system's electricity, heating, cooling, industry, and transportation sectors (Lund et al., 2021). The main goal is to thoroughly analyse the energy system to determine how different energy policies will affect it. Different energy systems are compared based on their price, technical and financial viability, and environmental impact of energy generation and use.

The modelling tool requires a set of inputs related to technical and economic aspects of the energy system's demand and supply side. The demand inputs are electricity, transport, cooling/heating, and fuel consumption for the energy sectors, such as industry and transport. As for the supply side, the model requires inputs such as generation unit capacities (fossil fuel plants, renewable energy sources, etc.), conversion unit capacities (electrolysers, CHP, etc.), costs (investment costs, lifetime, and percentage of investment), and various simulation strategies (technical simulation and market economic simulation). The user can additionally input the efficiency of the technologies used in the system's fossil fuel-based power plants and the capacity factor of RES technologies used. Figure 9 provides an overview of the inputs and outputs of the modelling tool, along with other relevant information.

EnergyPLAN has been employed as a research tool for different applications and geographical scopes. Some relevant works are already addressed in this master thesis in subchapter 2.2. Moreover, various studies employing EnergyPLAN are listed by Lund et al. (2021), providing valuable insights into the tool's functionality and showing its diverse range of applications.

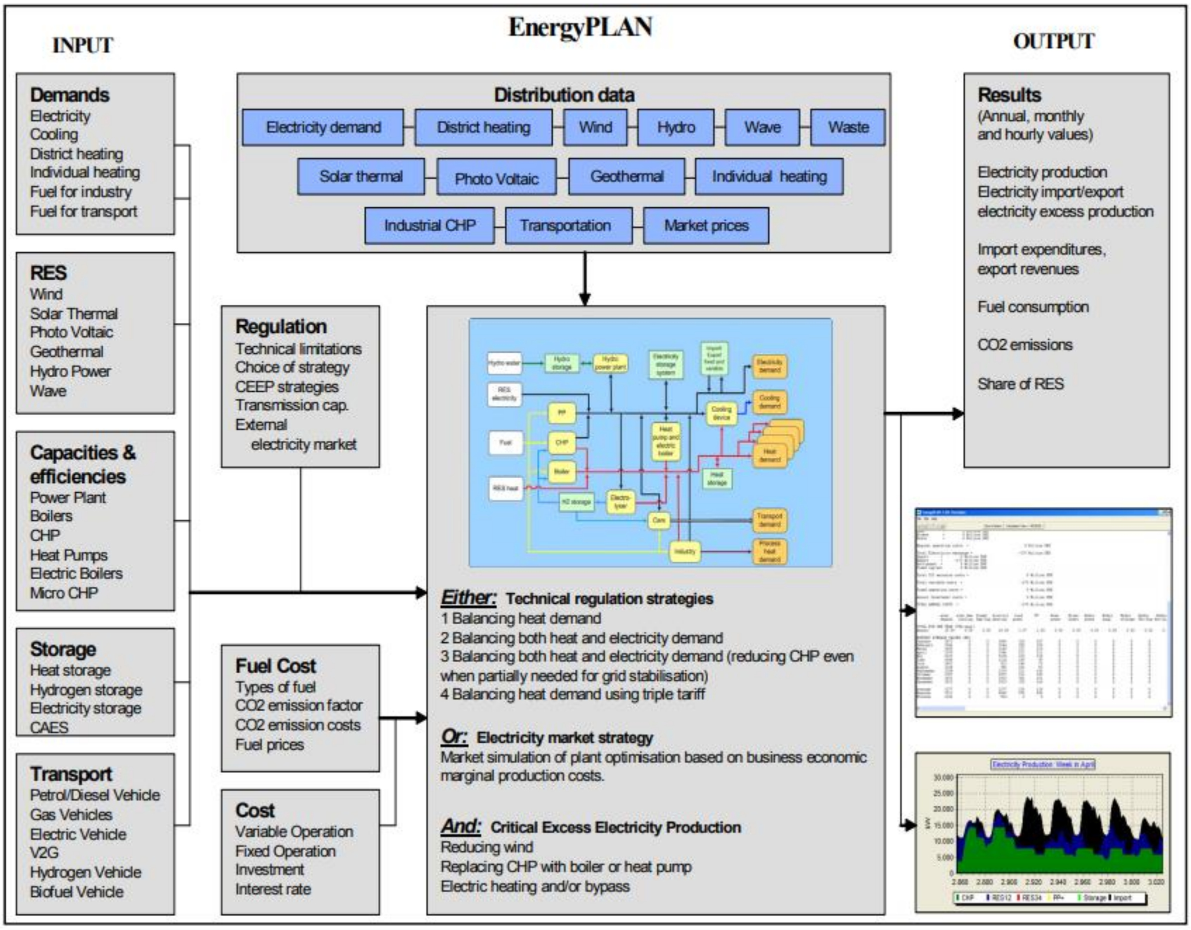

Figure 9 The structure of the EnergyPLAN
Source: Retrieved from Connolly (2010)

Meschede et al. (2022) emphasise EnergyPLAN's ascension as the primary simulation tool in this specialised domain, highlighting its popularity in 100% RE systems on islands. According to the authors, EnergyPLAN is the most commonly used research tool in island energy planning (Meschede et al., 2022).

This reputation as a preeminent choice in various studies is one of the reasons why it was chosen as the research tool for the current master's thesis. The recognition is further reinforced by Ferreira et al. (2020)’s recommendation of using an hourly approach to improve Santiago Island’s planning model accuracy in dealing with seasonality and intraday variability in the power system, with EnergyPLAN being appropriate for such purposes. Furthermore, the thesis explores the benefits of power and transport sector integration. As a result of its proven capabilities and alignment with research objectives, EnergyPLAN emerged as the right modelling tool for this research. The tool is easily downloaded from its official website (www.energyplan.eu), facilitating accessibility. For this master's thesis, version 16.22 was used.

The positive side of EnergyPLAN is its capacity to thoroughly examine the energy system, including the feasibility of various energy technologies from a technical and financial standpoint, the environmental effects of energy production and consumption, and the price of various energy strategies (Lund et al., 2021). Additionally, its capacity to simulate the operation of the energy system, which enables a more in-depth investigation, makes it a more qualified tool.

However, one disadvantage of EnergyPLAN is that obtaining and entering the large amount of input data needed for the model can take some time, especially if the energy system is complex. The model's accuracy is also influenced by the quality of the input data, which might be challenging to get. Furthermore, Nikzad (2019) points out other limitations that should be mentioned in this study. The author highlighted that the interconnector functionality of EnergyPLAN only accepts total power input and does not distinguish between different interconnectors, if any. Moreover, the lack of a thorough section on energy storage containing only a few input parameters was also discussed.

4.2. Selected Case Studies

In this research, EnergyPLAN was utilised to analyse and simulate the power and transport sectors to achieve the study's objective and answer the research questions. Four islands in the archipelago of Cabo Verde are examined in this master's thesis: Santo Antao (SA), Sao Vicente (SV), Sal (SL), and Santiago (ST). The decision to include these islands is because three of them dominate the countries' energy systems, producing 80% of the total electricity (ELECTRA, SA., 2021). Additionally, the inclusion of the island of SA in this study is strategically informed by its proximity to SV (approx. 12.5 km), making it an apt candidate for assessing the feasibility of an interconnected power system with SV.

The electricity generation in all the islands varies slightly throughout the year once there is no significant variation in climate. Figure 10 shows the load variation during different periods in the islands considered in this study. A summer and winter day were selected to demonstrate the load variation. SV and SA have relatively small variations between the seasons. SL and ST demonstrate a slightly increased production that might be related to the increase in demand stemming from tourism influx and amplified utilisation of domestic appliances during the hotter periods.

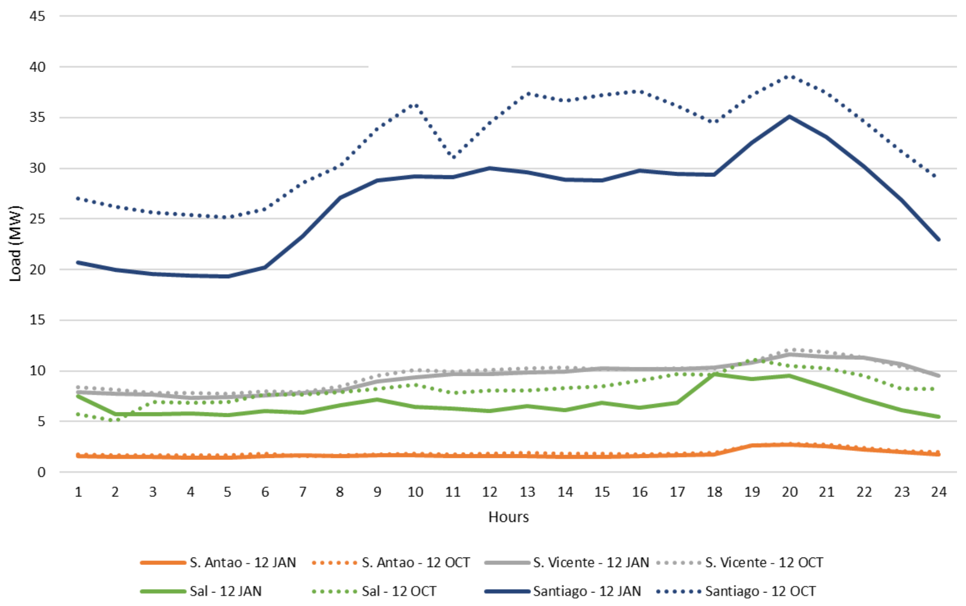

Figure 10 Hourly electricity load

Source: Obtained from (E. Nascimento & A. Cunha, personal communication, 12 May 2023)

SA had a power demand of approximately 16.7 GWh in 2019, met by two diesel and local wind power plants. SV has an estimated electricity demand of 80 GWh. The island's electricity is supplied by two fossil-fuelled power stations (diesel fuel and Fuel oil 380) and a local wind farm.

In SL, the supply of electricity is divided in two. A private concessionaire serves the hotels, while the remaining islands are served by the local company ELECTRA and Cabeólica, which supplies wind energy to all the islands. The aggregate demand, excluding the hotel's consumption, is 74.6 GWh. Due to data unavailability from the hotels, only regular demand was considered in this study.

ST has the highest electricity demand, with 244.4 GWh, constituting about 50% of the country's electricity. Four fossil-fuelled power stations (powered by diesel fuel and Fuel oil 380) and RE plants, namely solar photovoltaic (PV) and wind, provide the island electricity. Notably, the maximum peak demand reached in 2019 was 38 697 kW, recorded on the island of ST, followed by SV (13 600 kW), SL (13 000 kW) and SA (3 210 kW) (ELECTRA, SA., 2021). For a comprehensive overview of existing generation units and their installed capacity, refer to Table 3.

Table 3 Existing power generation units and electricity production

Island	Installed Capacity [kW]			Electricity Generation [kWh]		
	Thermal	**Wind**	**Solar**	**Thermal**	**Wind**	**Solar**
SA	8 456	500	2 250	15 226 975	1 388 697	57 192
SV	29 349	6 850	-	58 402 875	21 588 490	-
SL	16 856	7 650	3 735	51 522 633	20 173 670	2 867 594
ST	83 313	9 350	4 250	207 747 035	35 977 521	5 992 737

Source: ELECTRA, SA. (2019)

4.3. Data Collection

As mentioned, the EnergyPLAN system requires two types of input: technical and economical. The main inputs for the technical simulation are annual demand, production capacity and hourly distributions. The annual electricity demand load curves were obtained from (E. Nascimento & A. Cunha, personal communication, 12 May 2023). Moreover, fuel consumption and primary energy production data were obtained from Cabo Verde's energy balance, which only contains data about the overall country's energy mix. Data specific to the islands in the study was gathered from reports of national energy companies and governments' official documents, and assumptions were made to estimate the annual consumption per island. Table 4 lists the primary data type inputted used in the model and their respective source.

Table 4 Main data category and the respective source

Data Types	Data Sources
Electricity load demand Curves	(E. Nascimento & A. Cunha, personal communication, 12 May 2023)
Fuel consumptions	(MICE, 2019)
Solar and wind load distribution	(Pfenninger & Staffell, 2016)
Transportation historical data	(A. Costa, personal communication, 06/23; INE, 2020)
Power plants capacities	(ELECTRA, SA., 2020)
Fuel prices	(SGIE, 2023)
Population Statistics	(INE, 2019a, 2022a)
RE Potential	(Gesto Energia S.A., 2011b)
Economic Indicators	(INE, 2019b; World Bank Group, 2023)

The hourly distribution values were obtained from different sources. The annual load curve was obtained from national electricity company ELECTRA, and the hourly power output load for solar and wind energy was obtained from the free web platform www.renewables.ninja. Other required types of hourly distribution were obtained from the software database. Moreover, supplementary data for technical and economic analyses was searched and obtained from reliable sources within the body of existing literature.

4.4. Scenarios Development

EnergyPLAN simulates the energy system on an hourly resolution level over a year (Lund et al., 2021). Therefore, the first step was to collect historical data, such as data on demography, electricity generation and mix, load demand, and RES load curves, to simulate the selected islands' energy systems and validate the models' accuracy. The year 2019 was selected as the baseline due to data availability and its status as a pre-pandemic, i.e., the most recent year portraying Cabo Verde's real energy situation. Thenceforth, a baseline scenario, Scenario 0 (S0), was created for the reference year. A comparison of the scenario 0 outcomes with the actual data from 2019 served to validate the model.

After validating the EnergyPLAN modelling tool, the next step is to develop different scenarios to simulate the islands' energy systems in 2030. The scenarios are crafted to encompass key strategies that help the researcher achieve the study's objectives and address some research questions. Notably, a model considering the interconnection between SA and SV power's system is proposed within these scenarios, enhancing the complexity of the research. The following scenarios were modelled:

1. Scenario 1: Business-as-Usual scenario. This reference scenario serves as the benchmark by which comparisons are made. It limits its considerations to the currently in-use technologies, providing a baseline depiction. In addition to its fundamental principles, Scenario 1 also incorporates a subtle investigation. A small share of EVs is included for analysis purposes. Strategically, this inclusion intends to assess the effectiveness of the government's suggested plans for electrifying a subset of EVs.

2. Scenario 2: 100% RE-based system scenario. This scenario explores the viability of a power system totally dependent on RES. Its scope is expanded to include all land-borne transportation sectors in addition to the power sector.

The thorough explanations and procedural nuances relevant to creating these scenarios are provided in the following sections. However, before delving into that, a few shared inputs and assumptions were made, which will now be explained.

Developing future scenarios requires estimating future energy demand. The method used to forecast the demand is Multivariate Linear Regression (MLR), which establishes a relationship between a dependent variable and one or more independent variables (Liu & Li, 2023). Population statistics (INE, 2022b) and Gross Domestic Product (GDP) (World Bank Group, 2023) are employed as the independent variables, and electricity consumption ((ELECTRA, SA., 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022) is the dependent variable. The range of the data considered is from 2010 to 2022. To increase forecasting accuracy for electricity consumption, islands-specific data was utilised. The total GDP is proportionally distributed according to the share of each island as found in (INE, 2019b). The electricity demand for each island is therefore given by the equations below:

$$E_{Demand_{SA}} = 0.075 - 1.579 * 10^{-6} * Population_{SA} + 1.7 * 10^{-11} * GDP_{SA} \quad (1)$$

$$E_{Demand_{SV}} = -0.369 + 5.061 * 10^{-6} * Population_{SV} + 4 * 10^{-11} * GDP_{SV} \quad (2)$$

$$E_{Demand_{SL}} = -0.036 + 1.387 * 10^{-6} * Population_{SL} + 2 * 10^{-10} * GDP_{SL} \quad (3)$$

$$E_{Demand_{ST}} = -1.585 + 6.600 * 10^{-6} * Population_{ST} + 8 * 10^{-12} * GDP_{ST} \quad (4)$$

Biomass (charcoal and wood) consumption is expected to decline over the year in Cabo Verde as the population resorts to clean cooking utensils. The forecast was performed using the MLR method. Historical data collected from the National Institute of Statistics (INE) from 2010 to 2022 was used to estimate biomass consumption in 2030, including data regarding the share of households using charcoal and wood as their primary cooking utensil and the number of households (INE, 2019a, 2023). The biomass consumption is only assumed in the BAU scenario, and it is given by the equation below:

$$Share_{pop_{Conv_{cooking}}} = 1430.62 - 0.69 * year \mp 0.000081 * households \quad (5)$$

Due to a dearth of historical data, the annual fuel consumption for the transport and industry sector, is estimated using a straightforward approach. The annual compound growth rate of electricity demand of each island was ascribed to the different fuel types. It is acknowledged the consequences of inaccurate forecasts on energy systems. A study indicates a correlation between forecast accuracy and the degree of self-consumption, i.e., the smaller the prediction error, the less energy is fed into the grid (Putz et al., 2022). However, dependence on this strategy was necessary due to the limited data availability.

Regarding the transport sector, considering the inexistence of sector coupling with the power sector and only thermal conventional vehicles being used (except for ST, which already has a small share of EVs of dump charge systems), there is no need for hourly simulation. In this case, the model only requires the annual fuel demand for the transport sector. Therefore, the output will be the same as the input data for the transport sector. However, obtaining the energy balance with the annual oil consumption is possible, allowing for comparisons.

Both scenarios' input data for the transport sector in 2030 was constructed using guidelines and procedures taken from the literature. The starting point assumption is that there will be 4.6% more vehicles in 2030 than at the baseline period, corresponding to the last 5-year growth rate. Only land-borne vehicles are considered in this master’s thesis.

The annual diesel consumption by vehicle category was calculated using a weighted average approach, incorporating the forecasted diesel consumption. These results were then used to calculate the annual transport demand by vehicle category, considering diesel consumption and average fuel economy. Subsequently, the annual electricity consumption by vehicle category was estimated, considering a particular type of electric vehicle and its corresponding fuel economy. The input data utilised to build the scenarios and parameters used to calculate the annual transport demand can be found in the appendices section, Table 11- 14.

The industry and various sectors assume an efficiency improvement of 32.5%. The value is based on a study from Slabe-Erker et al. (2022), which found that energy consumption in this sector is expected to decrease by 10% for the European Union. Therefore, a higher share is assumed, considering the country’s reality. Given the current household cooking usage pattern, which only relies on butane gas use, it is assumed that scenario 2 is a shift towards electricity as the primary cooking source.

The cost calculation for scenario 1 considers the existing generation's cost (Table 5) plus the additional costs tied to the new installed capacities. As for scenario 2, all generation units' costs were based on the data from Table 6. These values were acquired from the literature (Alves et al., 2019; Baurzhan & Jenkins, 2017; Schröder et al., 2013) and reports for the country (Gesto Energia S.A., 2011b).

Table 5 Capital cost of existing generation units

Islands	Technology	Investment (€/kW)	Lifetime (Years)	O&M (% of Investment)
SA	Thermal Power Plants (Baurzhan & Jenkins, 2017)	470	25	4
	Onshore Wind	2 200	20	1
	Solar PV	3 250	30	1
SV	Thermal Power Plants (Baurzhan & Jenkins, 2017)	590	25	4
	Onshore Wind	1 911	20	2
	Solar PV	-	-	-
SL	Thermal Power Plants (Baurzhan & Jenkins, 2017)	585	25	4
	Onshore Wind	2 104	20	2
	Solar PV	467	30	3
ST	Thermal Power Plants (Baurzhan & Jenkins, 2017)	594	25	4
	Onshore Wind	2 200	20	2
	Solar PV	3 119	30	1

Sources: Unless stated otherwise, all the values were based on data from (Gesto Energia S.A., 2011b)

Table 6 Capital costs of new generation units

Technology	Investment Costs (€/kW)	Lifetime (Years)	Fixed O&M (% of Investment)	Variable O&M (€/MWh)
Solar PV	990	25	2	-
Onshore Wind (Schröder et al., 2013)	986	25	36.3 (€/kW)	-
Offshore (Schröder et al., 2013)	1224	25	110 (€/kW)	-
Wave Energy	4480	20	4.7	-
MSW power plant (Alves et al., 2020)	215.6 (€/MWh/year)	20	7.37	-

PSH (Gils & Simon, 2017)	10 (storage)	60	3	-
	640 (converter)	20		-
Submarine Cables (Coutinho et al., 2020)	31 M	40	3.5	-

Sources: Unless stated otherwise, all the values were retrieved from (Alves et al., 2019)

Furthermore, by combining the comprehensive results produced by models with qualitative/quantitative data retrieved from the available literature, the socioeconomic implications of the adoption or existence of a 100% RE-based system are assessed.

4.4.1. Scenario 1: Business-as-Usual Scenario

The BAU scenario (S1) is the simplest scenario. It is designed to assess the current RE target discussed in Chapter 3. The proposed scenario includes onshore wind and solar technologies already implemented in the islands in the study. In SV and SL, the optimum usage of the already available wind capacity was considered as a study revealed that their power output is being suppressed and unutilised (JICA, 2016). The strategy adopted is to increase the current installed capacity to increase the RE electricity production share by up to 50% in the island's power system. Additionally, following some strategies described in the country’s Nationally Determined Contribution (NDC) (MAE, 2021), a share of vehicles to be acquired by 2030 is assumed to be electrified, namely cars, busses and minibuses. It was assumed that all the electrified vehicles from this scenario agreed to participate in intelligent charge and V2G. The EVs are introduced in all scenarios to provide grid flexibility. Child et al. (2018) reference other benefits achievable by integrating EVs in energy systems, such as improving the efficiency and profitability of power grids, reducing GHG emissions for the transport sector, and offering potential income for vehicle owners.

4.4.2. Scenario 2: 100% RE-based System Scenario

The viability of full RES integration into the island's power system is examined in this scenario (S2). The modelled scenario relies heavily on the foundation of wind and solar technologies, taking advantage of the significant wind and solar potential across all islands. Notably, wave energy is added to the mix for SA, SV, and SL systems, broadening the range of RE. A thoughtful combination of offshore and onshore wind technology is considered in SV island due to its relatively higher wind potential. MSW (inc. waste from agriculture) is considered in SA, SV, and ST. The waste production capacity was estimated based on data from (Gesto Energia S.A., 2011b), and the heat values were retrieved from (Chen et al., 2016).

This scenario envisioned a complete shift, including electrifying all terrestrial transportation forms and incorporating some of them into V2G operations. It was assumed that busses, mini-vans, cars, and pick-ups agreed to participate in smart charge, and 50% agreed to participate in V2G. In addition, the scenario includes Pump Storage Hydro (PSH) technology to the energy mix of ST and SV, considering the crucial role the ESS plays, particularly in supporting high shares of RE integration. A feasibility study showing the feasibility of PSH in SV and ST served as the foundation for this inclusion. The storage and power capacity of the PHS are calculated based on the dimensions and capacity of the reservoir based on data from (Gesto Energia S.A., 2011a).

4.4.3. Interconnected Power System

The interconnection between SA and SV power systems is considered in both scenarios. According to Coutinho et al. (2020), 16 km of submarine cable is needed to interconnect these two islands. The demand is considered to be the sum of each island’s demand. The output from this model serves as the base for comparison with the separated system. The available endogenous resource from both islands is considered in the modelling.

Figure 11 Santo Antão and São Vicente islands proximity

Source: Retrieved from earth.google.com

5. RESULTS AND DISCUSSIONS

The first simulation results obtained through EnergyPLAN are compared with the data available on electricity production in the islands under analysis. As mentioned, this analysis seeks to determine the accuracy of the model's ability to reproduce island power plant performance.

Scenario 0 (S0) results demonstrate a creditable accuracy level, with minor differences observed. These differences are primarily concentrated on the islands of SL and ST, where a decrease of 0.8 GWh each in thermal generation is noted. These variations could be attributed to EnergyPLAN's preference for utilising RES over fossil fuels. The results can be observed in detail in Table 7.

Table 7 Comparison between EnergyPLAN results and existing data

Islands	**Thermal electricity produced [GWh]**		**RE electricity produced [GWh]**	
	Available Data [1]	EnergyPLAN	Available Data [1]	EnergyPLAN
SA	15.23	15.25	1.36	1.45
SV	58.4	58.42	21.59	21.57
SL	51.52	50.72	23.04	23.84
ST	207.75	206.95	36.63	37.44
TOTAL	**332.9**	**331.34**	**82.62**	**84.3**

Source: [1] ELECTRA, SA. (2020)

An increase in electricity demand is predicted for 2030, as shown in Table 8. The variation in electricity demand across the islands can be attributed to population growth and economic development disparities. SA is expected to experience a population decline and has a relatively lower economic status than the other islands, leading to a modest increase in electricity demand. On the other hand, the other islands are expected to experience population growth and contribute significantly to the country's economy; for instance, ST and SV have higher economic development and larger populations, resulting in a more substantial increase in electricity demand.

In Resolução nº 39/2019 (2019), it is estimated that the electricity demand for the four islands will be 657.54 GWh by 2030, considering a baseline scenario, which is 93 GWh higher than the results of this study. While the methodology adopted in this research only considered factors like electricity consumption historical data, population growth, and economic indicators, the variation in assumptions or data sources used in the two studies may explain this disparity. Possibly, this difference can be explained by their assumption that hotel facilities demand and tourism in the country will increase, which this study did not address directly.

Moreover, considering the government's policies and strategies to encourage EVs deployment and its potential benefits highlighted in several studies (Cantarero, 2019; Child et al., 2018) will cause demand increases and should be considered in further studies.

Table 8 Estimated Consumptions for 2030

Islands	Electricity [GWh]	Diesel [GWh]	Gasoline [GWh]	Jet [GWh]	Oil Industry [GWh]	Oil Households/ Services [GWh]	Biomass Households [GWh]
SA	24	26	6.20	-	7.23	16	32
SV	102	139	23	14.3	26	55.2	-
SL	97	81	19.3	164	22	45	-
ST	342	277	72	72	78	169	108

5.1. Scenario 1: Business as usual

The BAU scenario provides an overview of the technical and economic changes required for the islands to achieve 50% of electricity generation by 2030. As can be observed in Figure 12, compared to the 2019 figures, the installed capacity of energy sources shows significant variation among the four islands in the study. The power generation capacities reached a maximum of 131 MW in ST. Renewables now play a significant role in power generation, boasting 77 MW.

While experiencing a reduction in thermal power capacity, SV and SL maintained their wind capacity at a constant level from 2019. Solar energy now represents 29% and 34% of the installed capacity in SV and SL, respectively. The overall power generation capacity was 35 MW in SL and 34 MW in SV.

SA exhibited the most notable shift towards RES in 2030, with a substantial reduction in thermal power capacity and significant increases in wind and solar capacity. Power generation units reached about 12 MW, an increase of 32% compared to the base year.

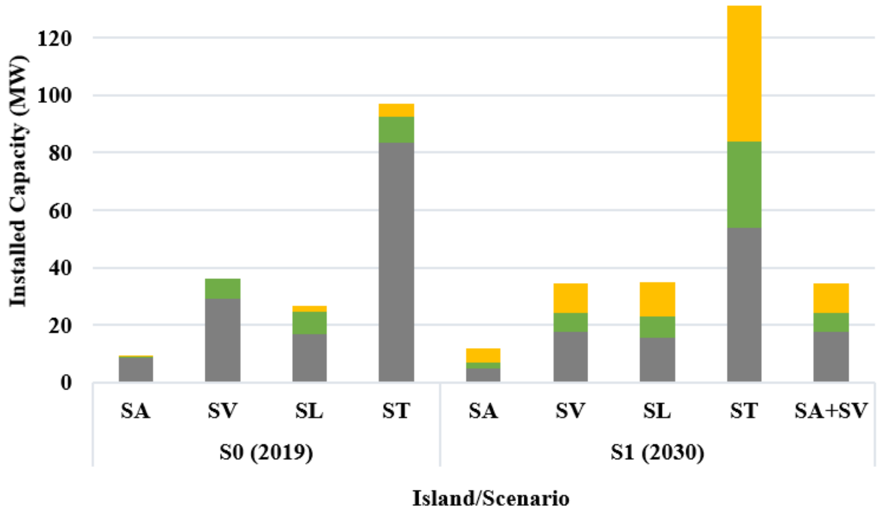

Figure 12 Installed capacities per scenarios

The interconnection strategy significantly optimises RES utilisation. The interconnection of SA and SV in 2030 (SA+SV) showcases a noteworthy outcome where the combined installed capacity of SA and SV equals SV's capacity alone, highlighting the potential benefit for efficiency gains through interconnected systems. Moreover, SV's installed capacity alone is sufficient to meet the cumulative energy demand of both islands. The surplus electricity from SV, once curtailed and unutilised considering the isolated power system, is now sufficient to meet SA’s demand. In Figure 13, it is possible to visualise the power generation mix from S1 and S0.

The results from S1 show a noticeable increase in RE generation on all islands. This intensification is especially noticeable in wind energy generation, which accounts for 19%, 28%, 31%, and 28% of the total power generated in SA, SV, SL and ST, respectively. Renewables now account for 50% of the power generation in all the islands.

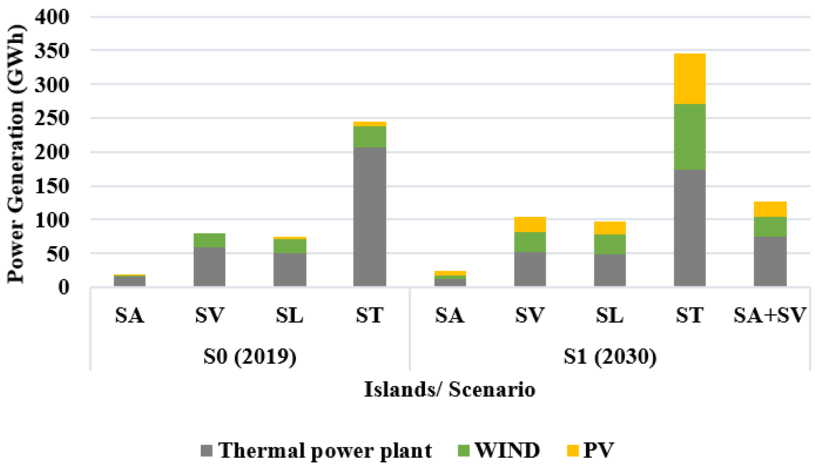

Figure 13 Energy generated by scenario

Table 9 illustrates the annual electricity usage taking into account the share of EVs envisaged in scenario 1. The results show beneficial accomplishments, such as reduction of CO2 emissions and fuel savings. The strategy of electrifying a share of new vehicle acquisition in all the islands results in a slight increase in electricity demand of 4.26 GWh, more than 50% of this share attributed to ST island. Consequently, there is a reduction in fuel consumption, namely diesel, in all the islands.

Table 9 Forecasted electricity demand for scenario 1

Islands	Vehicle Category	Share of vehicles consuming electricity [1]	Annual Electricity Consumption EVs (GWh/year) [2]
		S1 2030	**S1 2030**
SA	*Cars*	5%	0.202
	Buses	30%	0.004
	Mini Bus (Van)	40%	0.023
SV	*Cars*	5%	1.088
	Buses	30%	0.011
	Mini Bus (Van)	40%	0.013
SL	*Cars*	5%	0.629
	Buses	30%	0.007
	Mini Bus (Van)	40%	0.045
ST	*Cars*	5%	2.152
	Buses	30%	0.017
	Mini Bus (Van)	40%	0.072

The use of EV batteries led to a significant increase in the share of RE integration into the grid. However, it impacted the islands differently. For instance, simulations show that in SA island V2G operations have a higher degree of grid stabilization than in ST island. Moreover, the results indicated that ST Island stored more RE than SA Island. This variation in operations indicates that regional demand patterns, local grid conditions, and EVs availability must be considered when implementing V2G systems.

In Figure 12, it is possible to analyse the results of the average CO2 emission from the base year and BAU scenario. There is a reduction of 3 kt of CO2 emissions in SA, 8 kt in SV, 5 kt in SL and 26 kt in ST compared with the reference year. These savings are primarily attributable to reduced diesel consumption; hence, it was assumed that only diesel-fuelled vehicles were electrified.

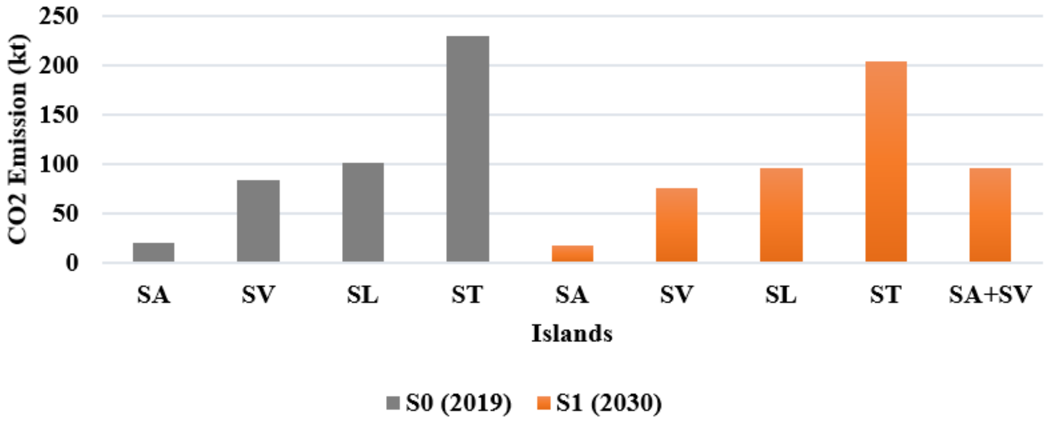

Figure 14 Average CO2 emission per scenario

Assuming a discount rate of 5% per year, the calculated average annual costs for the two scenarios are illustrated in Table 10. For scenario 1, the costs were calculated considering existing and new generation units and additional operation and maintenance costs (O&M). There is an increasing trend for the average system's cost mainly attributed to the over-installed RE capacity required to achieve the goal of 50% of RES electricity generation by 2030. The Variable O&M includes the calculated fossil fuel prices in 2030, namely, 0.65 €/l for diesel and 0.77 €/l for fuel oil.

Table 10 Annual investment costs

Islands/ Scenarios	Unit	SA	SV	SL	ST	SA+SV
Scenario 0	€/year	559 934	2 279 010	2 808 300	8 551 001	N.a.
Scenario 1	€/year	1 010 468	2 485 417	3 194 400	12 998 542	4 284 787

Similarly to the findings of Alves et al. (2020), the sum of the total annualized costs of the non-interconnected systems is lower than the total annualized costs of the interconnected system. From an economic perspective, interconnecting SA and SV islands may not be feasible due to the high investment costs.

A limitation of this study worth mentioning is the non-consideration of the decommissioning period of the thermal power plants in the cost calculation. The costs associated with retiring/ decommissioning these technologies, or even new installations, can have a significant impact on the overall economic assessment.

5.2. Scenario 2: 100% RE-based System Scenario

Figure 15 shows the installed capacities of the main technologies considered in scenario 2. Reaching a 100% RE-based system implies an over-installation of RES technologies. The installed capacity in ST peaked at 176 MW. According to potentials and capacities, wind and solar power dominate the islands' energy systems. Waste valorisation units are also included in SA, SV, and ST, diversifying their energy mix, while wave capacities are added in SA, SV, and SL islands.

Considering SV island, an important finding emerged from the simulations. The findings indicate that it will not be possible to achieve the island's goal of achieving 100% RE only with the current projects identified by Gesto Energia S.A. (2011b). In response, an additional 11 MW of offshore wind was incorporated into the island energy mix. However, this strategy might not be feasible considering the inexistent studies exploring this alternative. In fact, Pombo et al. (2022) suggested that offshore installations in the Cabo Verde are potentially complex given the large oceanic depth. While this study limited solar energy installation to 8 MW, in their study it reached a maximum of 160 MW in the Ref scenario (Pombo et al., 2022).

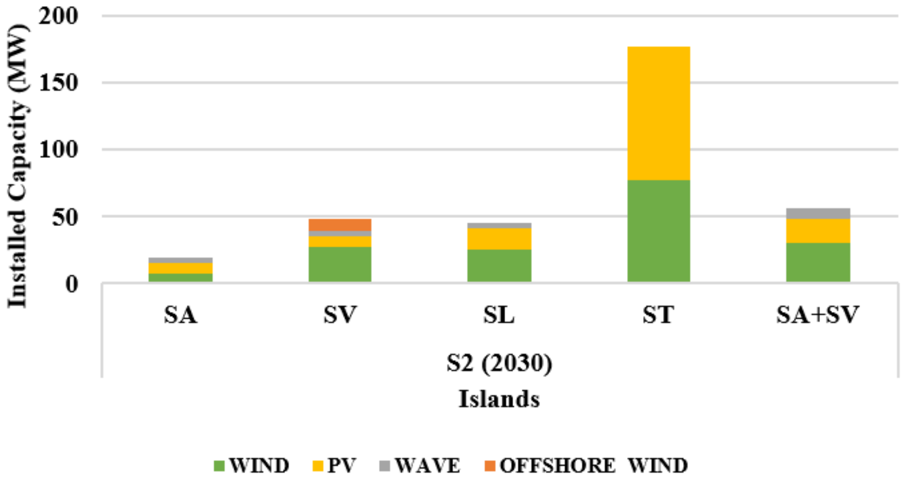

Figure 15 Installed capacities per island

Figure 16 shows the power generation mix in scenario 2. High shares of wind and solar energy characterise the scenario. With about 439 GWh generation considering all the islands, wind energy dominates the scenario. Solar and wave energy complements the energy mix of SA, SV, and SL, contributing to a more efficient and sustainable grid. Waste potential is relatively low. Therefore, it generates only a tiny amount of electricity. 2.15 GWh of electricity is generated from waste, assuming a 0.7% efficiency (0.02 GWh in SA, 0.27 GWh in SV, and 1.86 GWh in ST). In ST, results show that biomass contributes a mere 0.4% to the overall energy mix, which is a considerable difference from the findings of Ferreira et al. (2020) while planning a 100% RE power system for ST. In their analysis, biomass would represent 3% of the total power generated, playing a more significant role in the energy mix. Unfortunately, it is impossible to assess whether this resource is being underused in this work, considering that the authors did not clearly explain how the biomass availability was estimated. Nevertheless, simulations revealed that the strategic distribution of waste during times of lower demand can significantly strengthen grid stability.

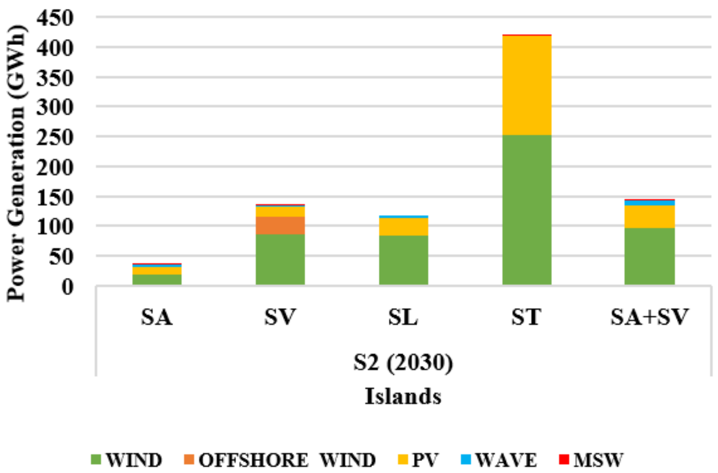

Figure 16 Power generation per island

The interconnected energy system encompassing SV and SA yields exciting insights. Similarly to the findings of Gils & Simon (2017), interconnecting the islands' power system reduces the overall size of the power plant and changes its composition. The combined endogenous RES results in a more diversified energy mix. Offshore wind parks are removed considering the lack of assessment regarding their feasibility. Compared to standalone systems, to achieve a 100% RE-based system, the islands' combined RE capacities generate more electricity with less installed capacity. For instance, SV generates 134 GWh with 49 MW, and SA generates about 36 GWh with approx. 19 MW installed capacity. Interconnected, their system would generate about 143 GWh with only 56 MW installed capacity.

The high fluctuation of the primary RE generation units, namely solar and wind, poses the main challenge for integrating high shares of RES into the islands' energy system. The demand and supply curve does not match continuously as expected. Figure 17 shows the imbalance between supply and demand on a day of low demand (winder period) and a day of high demand (summer period). It has been observed that the islands have low wind generation during high-demand periods. In this situation, wave and solar energy would have to meet all the demand. However, the low wave energy potential and technical problems related to nighttime periods can occur, and the need to supplement the system with ESS becomes imperative.

Meschede et al. (2022) suggest that sector coupling is inevitable on the road of 100% RE systems. Energy management must be adequately done to balance the supply and demand associated with energy storage from VRE. Storage system was only considered in SV, ST, and the interconnected model.

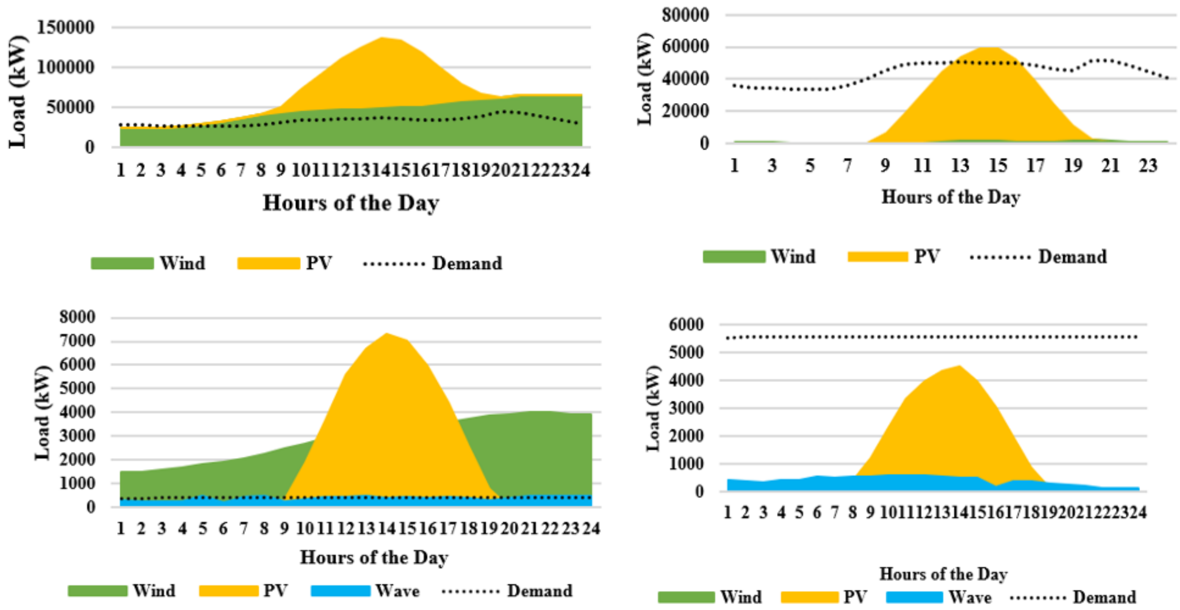

Figure 17 Hourly load variation

Illustration: The ST Island is shown in the top graph, and SA is represented in the lower graph. The conditions for a winter day are on the left, and those for a summer day are on the right (The samples were retrieved from a day in January and a day in August).

Table 11 shows the share of RE energy achieved with the proposed technologies and the Critical Excess Electricity Production (CEEP) in each island. The CEEP values can be used to determine the storage size needed and implement strategies to use this energy to balance the system smartly.

Table 11 Results from the models for the Share of RES and CEEP

	Scenario 2				
Islands	**SA**	**SV**	**SL**	**ST**	**SA+SV**
Share of RE (%)	100	100	100	100	100
CEEP (GWh)	5.44	22.32	16.82	58.29	15.05

Results indicate that the integration of PSH into the system did not impact the system dynamics, with its primary role being the improvement of grid stability. A discharge capacity of 1.49 GWh and 2.06 GWh in SV and ST was found, respectively. The share of storage output from the PHS EVs battery and EVs batteries can be visualised in Figure 18.

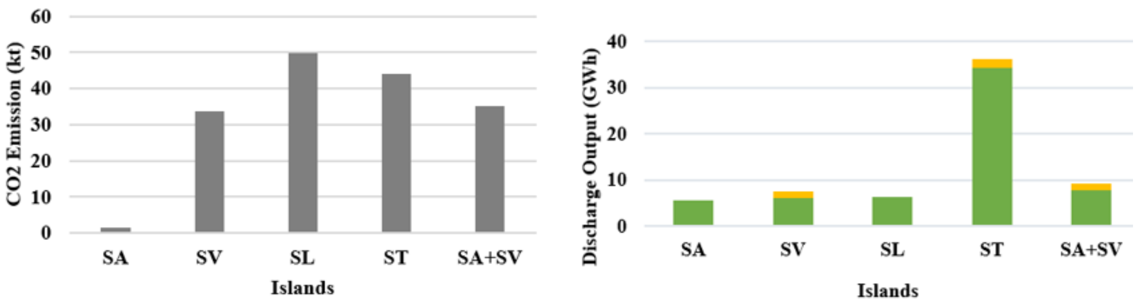

Figure 18 Average CO2 emissions and discharge output

JICA (2016) suggests that the introduction of PHS must be looked at carefully. The authors pointed out significant concerns about the economic operation of the PHS power plant. The economical operation of a PHS power plant relies heavily on the availability of excess of electricity for efficient pumping and a well-suited load pattern that facilitates frequent and efficient power generation during discharge phases (JICA, 2016). The authors highlighted the critical need to recognize that the efficiency of a PHS plant is compromised when the time gap between peak demand hours and non-peak hours is minimal, and RE output remains consistent. As an alternative they suggest, batteries for long-cycle fluctuation control (JICA, 2016), which are excellent in terms of cost and portability.

Yue et al. (2021) highlighted in their work the role of hydrogen as medium to long-term energy storage. Hydrogen is suitable to deal with energy time shifting and seasonal variation. In this context, hydrogen emerges as a potential solution for energy storage considering the high wind energy seasonality.

In the Appendices section, Table 15 to 19 contains all the parameters used for transport electricity demand forecast and parameters used to define V2G operation in the model. With a complete electrification of land-borne transport electrified, it would result in a surge in energy demand of 126.23 GWh considering the four islands. ST, as the home of 61% of all Cabo Verde’s terrestrial transportation, would account for approximately 55% (69.13 GWh) of this boosted demand, followed by SV (32.89 GWh), SL (18.44 GWh), and SA (5.76 GWh).

Results show that extending smart charge operations to a larger range of transport types could increase the storage capacity offered by EVs. However, this possibility could be limited by the intention of private vehicle owners to participate in V2G voluntarily. The discharge output (see Figure 18) is also conditioned by the low transport demand, especially in the small islands. Considering ST island’s size and relatively higher transport demand, massive transport sector electrification could represent an excellent opportunity to integrate more VRE. Furthermore, the simulations showed that employing an effective smart charging approach, greatly improves the effectiveness of V2G operations. For instance, different smart charging hourly distribution patterns led to different discharge outcomes, highlighting the possibility for higher RE penetration and grid flexibility when an optimised charge-discharge scheme is in line with the demand patterns of the islands.

This scenario would result in a decrease of 305 kt of CO2 emissions compared to S0, while considering the four islands. However, the other transportation modes still greatly contribute for emissions. In Cabo Verde, marine and aviation transportation play a pivotal role in inter-island communication, albeit with varying degrees of influence on each island's emissions profile. For example, SL for being a touristic island, receives more domestic flights, resulting in higher Jet fuel consumption and emissions. Similarly, marine transportation is more pronounced in SV hence the reason for having higher emission levels than ST. These results underscore the need for island-specific strategies in transport sector decarbonization. While emissions reductions can be achieved through initiatives such as transport electrification, fuel efficiency, and alternative fuels, it is crucial to adopt these strategies to the particular transportation demands and patterns of each island.

Due to time constraints, this research has focused solely on analysing the possible gains of EVs within the islands' energy system. However, EnergyPLAN can be used to explore further strategies for transport sector decarbonization, such as the production of biofuels, biogas, and hydrogen. The surplus of electricity caused by the over-installation of RE technologies required to reach a 100% RE-based system can offer an opportunity to produce synthetic fuel, which can replace fossil fuels. Wärtsilä Corporation (2020) explored a decarbonization scenario featuring power-to-fuel technologies on a medium-sized Mediterranean island. Their analysis revealed compelling benefits, including efficient conversion of the electricity excess into biofuels and cost savings compared to the BAU scenario. This suggests an opportunity for future studies to explore similar opportunities in Cabo Verde Islands.

The interconnected model combines SV and SA energy consumption patterns; therefore, the increase in electricity demand for the transport sector and the respective CO2 annual emissions reduction results from the summation of both island's inputs.

Table 12 shows the annualised investment costs from scenario 2 as well as the Levelized Cost of Electricity (LCOE) figures considering the overall energy system of each island under the S1 and S2 scenarios. The LCOE calculation from scenario 1 indicates that thermal power plants have the lowest LCOE in all four islands. Wind energy has the second lowest LCOE in the islands of ST and SA. While in SL and SV solar energy is the most cost-effectives.

Considering scenario 2, wind energy has the lowest LCOE compared to solar energy, with an average of 0.023 €/KW. Solar is the second most cost-effective technology, with varying LCOE values across islands. SV has the highest wave and offshore wind LCOE, indicating that these technologies may be less economically viable.

Compared to the BAU scenario, scenario 2 presents higher annualised investment costs in all the islands. This is due to the over-installation of RE capacities and the diversified energy mix. Other costs associated with transport sector, such as EVs supply equipment, batteries and charging infrastructures must be considered in future studies. Likewise, costs associated with the construction of PHS must be taken in consideration. The high investment costs related to the 100% RE-based system and the interconnected proposition is indicated to result in a prohibitive cost for Cabo Verde (Ferreira et al., 2020; Nordman et al., 2019). Nevertheless, these values can be revised, and cost-intensive strategies can be reduced by model improvements and efficient use of ESS.

Table 12 Levelized cost of electricity for overall energy systems

Islands/ Scenarios	Unit	SA	SV	SL	ST	SA+SV
Scenario 1	€/KW	0.041	0.024	0.047	0.038	0.034
Scenario 2	€/KW	0.070	0.039	0.037	0.039	0.060
Annual Investment costs S2	€/year	2 482 580	5 267 588	4 296 820	16 415 292	8 602 791

While it may currently seem economically challenging for Cabo Verde to achieve its goal of attaining a 100% RE, this should not discourage the country from making progress towards this ambition. Instead, this just underscores the need for research and development initiatives to seek for more efficient and cost-effective strategies for the widespread deployment of RES. Higher shares of RES in the islands would offer numerous positive socio-economic benefits such as lower dependence on fossil fuels, consequently reducing the high vulnerability to oil price fluctuation and enhancing energy security; would spare the country from the volatilities from the global fuel markets and it offers job opportunities gains through the construction, operation and maintenance of RE projects. Additionally, the expansion of RE projects can contribute to electricity access, improving the population's quality of life.

Given that EVs typically have lower operating costs than conventional fossil-fuel-powered vehicles, the adoption of EVs can minimise transportation costs and improve inter-island communication. Additionally, since Cabo Verde is a tourist destination, it can benefit from portraying itself as an environmentally friendly nation and, in turn, boost the tourism sector, which can also generate more job opportunities.

5.3. Key Policies Recommendation

Cabo Verde's government should encourage public and private investments in renewable projects to speed up the transition to clean energy. Financial incentives and tax benefits for investors in RE can facilitate this process.

The International Renewable Energy Agency (IRENA) (IRENA, 2016) has developed a number of policy recommendations for islands, including the case of Cabo Verde. The impact of mini-grids in a locality in SA is highlighted as a case of success in showcasing other electrification possibilities rather than grid extension (IRENA, 2016). Therefore, this strategy can still be applied in other remote regions of SA and ST that still lack access to electricity, giving a valuable potential to improve RE penetration. Moreover, mini-grid expansion can also contribute to economic growth by creating job opportunities.

As RE generation increases, grid infrastructure and management systems investments are paramount. These investments are critical for efficiently balancing demand and supply. Concurrently, research and development of appropriate energy storage technologies should be encouraged to improve grid stability. V2G improves grid stability and offers an excellent opportunity to reduce fossil fuel consumption and CO2 emissions. Incentives for EV owners, such as reduced electricity rates or financial awards, should be provided to encourage participation in V2G schemes. Moreover, participation in V2G services by more road vehicles and other vehicle types, including boats, can reduce the need for other energy storage technologies (Child et al., 2018).

Exploring sector coupling options, where excess energy is used for other sectors, such as transportation or desalination, should be considered. The possibility of coupling the energy and water supply systems in SV was analysed by Segurado et al. (2011). The excess electricity generated from wind energy, once rejected, is now utilised to supply the desalination plant, attaining higher shares of RE (Segurado et al., 2011). This strategy could be applied to other islands experiencing comparable water and electricity consumption increases.

While the heating sector may not be of significant importance in Cabo Verde's energy system due to its limited use in small-scale industries and residential buildings, cooling is becoming increasingly important, especially during summer periods. The issue can be addressed through measures to reduce energy consumption in the cooling sector while maintaining thermal comfort. This can be accomplished using energy-efficient buildings and cooling technology.

The seasonal demand caused by tourism on the islands, which can create additional complexity for electricity generation and supply, needs to be considered in the energy planning of Cabo Verde. Energy-efficient hotels and resorts can be promoted using incentives and certifications. Electric Mobility also constitutes an opportunity to promote V2G programs which can enhance grid stability. Furthermore, considering their tourism potential, the islands allow for installing demand-side management systems aimed at hotels to promote lower energy consumption during peak periods.

6. CONCLUSIONS

The use of fossil fuels in island nations poses significant challenges to their economies and environment. Luckily, their vast renewable resources can enable them to decrease this dependence on fossil fuels, fostering significant self-sufficiency. This master's thesis aimed to explore alternatives to increase the penetration of renewable sources in Cabo Verde Islands' energy system. Four islands of the archipelago - Santo Antão, São Vicente, Sal, and Santiago - were chosen as case studies. The findings provide valuable insights into the technical feasibility and economic viability of transitioning towards higher RE penetration.

Two scenarios were proposed, and a comparative analysis was made considering technical, economic, and environmental aspects. The conducted case study highlighted the significant potential for harnessing renewable energy. During this research, two main challenges were faced. Firstly, the dearth of island-specific data, which requires the formulation of several assumptions based on several studies to create a useful dataset to work. And secondly, time restrictions limited the analyses that would have enhanced this research.

The research showed that achieving a 50% renewable energy penetration by 2030 is technically possible based on the country's existing strategic energy plans for the power and transport sectors. However, such a transition would require significant investments in new capacities, grid infrastructure enhancements, and energy storage solutions to manage renewable energy generation and consumption fluctuations effectively.

Similarly, the simulation of integrating a 100% renewable energy system demonstrated the feasibility of such transformation considering the installation of renewable projects already identified for the country, except São Vicente, which required the installation of additional generation units. Nevertheless, the analysis stressed the crucial role of storage systems in maintaining grid stability and optimising RE utilisation. Results show a critical excess of electricity generation in several months, which can be assessed if it is sufficient to balance the system in periods of low supply, considering an adequate storage system. The storage system adopted in the islands of São Vicente and Santiago represents considerable potential, even though their implementation constitutes additional costs to the system.

In this context, the concept of power-to-hydrogen can serve as an effective energy storage method, offering the possibility of converting excess electricity into hydrogen (Goldmeer, 2018). This approach aligns with the country's seasonal RE generation patterns and enables long-term energy shifting. The literature also supported the feasibility of hydrogen production as a means of sustainable energy storage (Goldmeer, 2018), suggesting a direction for future research within the Cabo Verde Islands.

Adopting V2G operations represented another viable strategy for grid stabilisation, albeit with different levels of impact across different islands and scenarios. For instance, V2G significantly impacted Santiago allowing higher shares of renewables in the system while in Santo Antão the discharge output is lower, but it contributes more to grid stabilization.

The potential for an interconnected power system between Santo Antão and São Vicente islands was also investigated in the study. This system could achieve larger RE shares with less installed capacity. However, submarine cable and construction costs pose the main challenge for the country. Nevertheless, their interconnection presents an excellent opportunity for an increase in RES integration, especially when considering Santo Antão’s geographic conditions and uneven population distribution, which might pose challenges for the deployment of RE, especially solar farms.

The results demonstrated the technical potential of transitioning towards a higher renewable energy share, but the country's financial reality limits the economic viability of such a change. As a developing country that relies significantly on external aid, it may be challenging to get enough funding for the extensive deployment of RE. However, this obstacle creates opportunities for foreign trade and international partnerships to support Cabo Verde's transition to a more sustainable energy.

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8. APPENDICES

Table 13 Main input data considered in the models

Islands	Parameters	Unit	Scenarios S0: BAU (2019)	Scenarios S1: BAU (2030)	Scenarios S2: 100% RE (2030)
SANTO ANTÃO	*Electricity Total*	GWh /yr	16.7	24.23	29.76
	Electricity Demand	GWh /yr	16.7	24	24
	Electricity Transport	GWh /yr	-	0.23	5.76
	Transport Fuel Demand total	GWh /yr	31.2	31.98	0.52
	Diesel	GWh /yr	25.2	25.78	0.52
	JP (Jet Fuel)	GWh /yr	-	-	-
	Gasoline	GWh /yr	6	6.2	-
	Industry Fuel Demand total	GWh /yr	22.1	7.23	7.23
	Oil products and derivatives	GWh /yr	7	7.23	7.23
	Biomass	GWh /yr	15.1	-	-

	Fuel Various Demand (inc. households) total	GWh /yr	59.2	48	16
	Oil products and derivatives	GWh /yr	15	16	16
	Biomass	GWh /yr	44.2	32	-
SÃO VICENTE	*Electricity Total*	GWh /yr	79.99	103.11	134.89
	Electricity Demand	GWh /yr	79.99	102	102
	Electricity Transport	GWh /yr	-	1.11	32.89
	Transport Fuel Demand total	GWh /yr	173.9	175.16	109.38
	Diesel	GWh /yr	136	137.89	95.08
	JP (Jet Fuel)	GWh /yr	14	14.3	14.3
	Gasoline	GWh /yr	22.9	23.41	-
	Industry Fuel Demand total	GWh /yr	25	26	26
	Oil products and derivatives	GWh /yr	25	26	26
	Biomass	GWh /yr	-	-	-
	Fuel Various Demand (inc. households) total	GWh /yr	54	55.2	55.2
	Oil products and derivatives	GWh /yr	54	55.2	55.2
	Biomass	GWh /yr	-	-	-
SAL	*Electricity*	GWh /yr	74.56	97.68	115.44
	Electricity Demand	GWh /yr	74.56	97	97
	Electricity Transport	GWh /yr	-	0.68	18.44
	Fuel for transport total	GWh /yr	257.4	263.62	172.84
	Diesel	GWh /yr	78.6	80.32	8.83
	JP (Jet Fuel)	GWh /yr	160	164	164
	Gasoline	GWh /yr	18.8	19.3	-
	Fuel industry total	GWh /yr	21	22	22
	Oil products and derivatives	GWh /yr	21	22	22
	Biomass	GWh /yr	-	-	-
	Fuel Various Demand (inc. households) total	GWh /yr	44.2	45	45
	Oil products and derivatives	GWh /yr	44.2	45	45
	Biomass	GWh /yr	-	-	-

SANTIAGO	*Electricity*	GWh /yr	244.40	344.26	411.13
	Electricity Demand	GWh /yr	244.38	342	342
	Electricity Transport	GWh /yr	0.02	2.26	69.13
	Fuel transport total	GWh /yr	408.6	418.76	113.21
	Diesel	GWh /yr	269.1	274.76	41.21
	JP (Jet Fuel)	GWh /yr	70	72	72
	Petrol	GWh /yr	69.5	72	-
	Fuel industry total	GWh /yr	126	78	78
	Oil products and derivatives	GWh /yr	76	78	78
	Biomass	GWh /yr	50	-	-
	Fuel Various Demand (inc. households) total	GWh /yr	310.5	277	169
	Oil products and derivatives	GWh /yr	163.5	169	169
	Biomass	GWh /yr	147	108	-

Table 14 Installed capacity per scenario (KW)

Islands	Technologies	Scenarios		
		S1: BAU		**S2: 100% RE**
		(2019)	**(2030)**	**(2030)**
SA	*Thermal Power Plant*	8456	4900	-
	Solar PV	80	5000	8300
	Onshore Wind	500	2000	5000
	Offshore Wind	-	-	-
	Wave Power	-	-	4000
	Biomass (MSW)	-	-	0.029*
	Hydro Pump Storage	-	-	-
SV	*Thermal Power Plant*	29349	17500	-
	Solar PV	-	10000	8000
	Onshore Wind	6850	6850	27000
	Offshore Wind	-	-	11000
	Wave Power	-	-	4000
	Biomass (MSW)	-	-	0.383*
	Hydro Pump Storage	-	-	178*
SL	*Thermal Power Plant*	16856	15500	-
	Solar PV	2250	12000	16000
	Onshore Wind	7650	7650	25000

	Offshore Wind	-	-	-
	Wave Power	-	-	4000
	Biomass (MSW)	-	-	-
	Hydro Pump Storage	-	-	-
ST	*Thermal Power Plant*	83314	54000	-
	Solar PV	4250	47000	100000
	Onshore Wind	9350	30000	77000
	Offshore Wind	-	-	-
	Wave Power	-	-	-
	Biomass (MSW)	-	-	2.66*
	Hydro Pump Storage	-	-	896*
SA+SV	*Thermal Power Plant*	N.a.	17500	-
	Solar PV	N.a.	10000	18000
	Onshore Wind	N.a.	6850	40000
	Offshore Wind	N.a.	-	-
	Wave Power	N.a.	-	8000
	Biomass (MSW)	N.a.	-	0.401*
	Hydro Pump Storage	N.a.	-	178*

* Givern in GWh

Table 15 Technical specifications of electric vehicles considered in S1 and S2

Electric Vehicle	Power Rate (kW)	Battery Capacity (kWh)	Fuel Economy (km/kWh)
2022 Volkswagen ID.4 AWD Pro (The Car Connection, 2022)	125	77	5.1
2023 Chevrolet Bolt EV (Chevrolet, n.d.)	150	65	5.7
Zero S ZF7.2 Motorbike (Cantarero, 2019)	1.3	7.2	13.5
BYD K9 Electric Bus (BYD Motors Inc, 2017)	80	324	1.3
Zenith Motors Van (Cantarero, 2019)	6	51.8	2.5
Rivian R1T (Rivian, 2023)	562	135	3.51
BYD Class 8 Trucks (Cantarero, 2019)	80	188	0.8

Table 16 Vehicle to Grid Parameters

ISLAND	Scenario	V2G Battery Capacity (MWh)	Capacity of connection (grid-to-battery) (KW)	Capacity of connection (battery-to-grid) (KW)	Smart Charge (GWh/yr)	Share of cars during peak demand	Share of parked cars grid connected
SA	S1	8	9 510	4 755	0.23	0.2	0.8
	S2	80	165 107	82 553	4.35	0.2	0.8
SV	S1	18	26 029	13 014	1.11	0.2	0.8
	S2	436	912 843	456 422	23.05	0.2	0.8
SL	S1	9	11 204	5 602	0.68	0.2	0.8
	S2	195	417 635	208 818	13.59	0.2	0.8
ST	S1	64	93 950	46 975	2.24	0.2	0.8
	S2	1521	3 093 807	1 154 577	44.56	0.2	0.8
SV+SA	S1	26	35 539	17 769	1.34	0.2	0.8
	S2	515	1 077 950	538 975	27.40	0.2	0.8

Table 17 Transport demand statistics per vehicle type and scenario

Islands	Vehicle Category / Scenario	Annual transport demand (km/year)[1]	Share of vehicles consuming diesel[2]		Fuel Economy (km/l)[3]	Annual Diesel Consumption (l/year)[4]
		2030	S1: 2030	S2: 2030		2030
SA	*Cars*	20 404 073	75%	0%	11.61	1 757 998
	*Motorcycles**	359 388	0%	0%	18.71	19 212
	Buses	15 916	70%	0%	1.57	10 118
	Mini Bus (Van)	144 796	60%	0%	8.42	17 201
	Pick-ups	1 697 066	90%	0%	9.37	181 117
	Trucks	1 098 745	100%	0%	8.42	130 526
	HDVs: Construction*	11 383	85%	0%	2.25	5 059
SV	*Cars*	110 104 915	75%	0%	11.61	9 486 550
	*Motorcycles**	9 356 712	0%	0%	18.71	1 923 846
	Buses	46 072	70%	0%	1.57	29 289
	Mini Bus (Van)	82 183	60%	0%	8.42	9 763
	Pick-ups	8 763 708	90%	0%	9.37	935 294

	Trucks	7 273 225	100%	0%	8.42	864 025
	*HDVs**: Construction*	43 933	85%	0%	2.25	19 526
SL	*Cars*	63 632 009	75%	0%	11.61	5 482 482
	*Motorcycles**	7 695 497	0%	0%	18.71	1 111 832
	Buses	31 363	70%	0%	1.57	19 938
	Mini Bus (Van)	279 721	60%	0%	8.42	33 230
	Pick-ups	5 679 219	90%	0%	9.37	606 107
	Trucks	3 401 408	100%	0%	8.42	404 071
	*HDVs**: Construction*	23 925	85%	0%	2.25	10 633
ST	*Cars*	217 870 180	75%	0%	11.61	18 771 518
	*Motorcycles**	28 638 150	0%	0%	18.71	3 806 811
	Buses	75 224	70%	0%	1.57	47 821
	Mini Bus (Van)	447 280	60%	0%	8.42	53 135
	Pick-ups	13 308 130	90%	0%	9.37	1 420 291
	Trucks	17 891 198	100%	0%	8.42	2 125 389
	*HDVs**: Construction*	64 559	85%	0%	2.25	28 693

[1] Based on the average fuel economy and annual diesel consumption.
[2] Authors own assumptions. The complementary share of vehicles is assumed to consume gasoline instead of diesel in scenario 1. Scenario 2 Assumes all the vehicles to be electrified.
[3] Based on the average fuel economy of major vehicle categories (AFDC, 2020)
[4] Authors own assumptions.
* Motorcycles are assumed to consume gasoline.
** Heavy Duty Vehicles

Table 18 Electricity demand per vehicle category and scenario

Islands	Vehicle Category / Scenario	Share of vehicles consuming diesel			Annual Electricity Consumption (GWh/yr)	
		S0:2019	**S1: 2030**	**S2: 2030**	**S1 2030**	**S2 2030**
SA	*Cars*	80%	75%	0%	0.202	3.80
	Motorcycles	0%	0%	0%		0.03
	Buses	100%	70%	0%	0.004	0.01
	Mini Bus (Van)	100%	60%	0%	0.023	0.06
	Pick-ups	90%	90%	0%		0.48
	Trucks	100%	100%	0%		1.37
	HDVs: Construction	85%	85%	0%		0.01
SV	*Cars*	80%	75%	0%	1.088	20.49
	Motorcycles	0%	0%	0%		0.69

	Buses	100%	70%	0%	0.011	0.04
	Mini Bus (Van)	100%	60%	0%	0.013	0.03
	Pick-ups	90%	90%	0%		2.50
	Trucks	100%	100%	0%		9.09
	HDVs: Construction	85%	85%	0%		0.05
SL	*Cars*	80%	75%	0%	0.629	11.84
	Motorcycles	0%	0%	0%		0.57
	Buses	100%	70%	0%	0.007	0.02
	Mini Bus (Van)	100%	60%	0%	0.045	0.11
	Pick-ups	90%	90%	0%		1.62
	Trucks	100%	100%	0%		4.25
	HDVs: Construction	85%	85%	0%		0.03
ST	*Cars*	80%	75%	0%	2.152	40.54
	Motorcycles	0%	0%	0%		2.12
	Buses	100%	70%	0%	0.017	0.06
	Mini Bus (Van)	100%	60%	0%	0.072	0.18
	Pick-ups	90%	90%	0%		3.79
	Trucks	100%	100%	0%		22.36
	HDVs: Construction	85%	85%	0%		0.08

Table 19 Number of vehicles per scenario

Islands	**Vehicle Category**	**Scenarios**	
		S0 2019 [1]	**S1 & S2 2030** [2]
SA	*Cars*	1 737	1 817
	Motorcycles	352	368
	Buses	10	15
	Mini Bus (Van)	17	27
	Pick-ups	179	181
	Trucks	129	120
	HDVs: Construction	5	13
SV	*Cars*	9 717	10 162
	Motorcycles	1 971	2 061
	Buses	30	50
	Mini Bus (Van)	10	20
	Pick-ups	958	981
	Trucks	885	914
	HDVs: Construction	20	25
SL	*Cars*	4 125	4 314
	Motorcycles	836	875

	Buses	15	30
	Mini Bus (Van)	25	50
	Pick-ups	456	522
	Trucks	304	223
	HDVs: Construction	8	20
ST	*Cars*	35 328	36 946
	Motorcycles	7 164	7 493
	Buses	90	120
	Mini Bus (Van)	100	120
	Pick-ups	2 673	2 774
	Trucks	4 000	4 140
	HDVs: Construction	54	80

[1] Based on transport historical data obtained from (A. Costa, personal communication, 06/23)