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MASTER THESIS

Topic:

OPTIMIZING ENERGY PROVISION ON SMALL ISLANDS INCLUDING A DESALINATED WATER CONSTRAINT APPLIED TO CAPE VERDE

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ABSTRACT (ENGLISH VERSION)

This thesis proposes a new approach for energy provision applicable to all small islands including desalinated water constraints. It includes the generation of energy through renewable energies and/or synfuel; electrolyzer, fuel cell, and desalination plants as conversion technologies as well as storage in batteries, synfuel tanks, and/or hydrogen tanks. With the objective of determining the most cost-effective configuration to deliver energy in small islands, the developed approach considers several transmission alternatives: (i) subsea direct current power cables, (ii) specific vessels delivering either synfuels or hydrogen, (iii) hydrogen pipelines and (iv) cargo, containers and/or fuel trucks carrying energy carriers loaded into existing Roll on – Roll off ships or ferries routes. Three scenarios were considered: (i) a baseline scenario that represents existing energy systems on islands, (ii) a Mixed-Use scenario that only includes existing ferry routes for synfuel delivery, and (iii) 100% RE where the 2050 demand is met sustainably. Moreover, a new criterion for seawater reverse osmosis desalination site selection was also developed thus limiting any green hydrogen production to the maximum eligible land. By using Cape Verde to validate the model, results show that land eligibility ranges from 0 to 42% and that slope, wetlands, and isolated settlements are crucial criteria. Also, the most cost-effective scenario is the Baseline which requires an investment of 246 million euros. Due to several reasons, the Mixed-Use scenario increases the investment by a factor of 4 while the 100% RE scenario overcomes the 5 billion euros mark. Among the RE sources, there’s a clear dominance of onshore wind over PV being the most deployed source in all scenarios.

Keywords: Cape Verde; Renewable Energies; MILP optimization; Energy provision on islands; Desalination site selection.

RÉSUMÉ (FRENCH VERSION)

Ce mémoire propose une nouvelle approche de fourniture d'énergie applicable aux petites îles en tenant compte des contraintes liées à l'eau dessalée. Elle inclut la production d'énergie à partir d'énergies renouvelables et/ou de carburants synthétiques; l'électrolyseur, la pile à combustible et les usines de dessalement comme technologies de conversion, ainsi que le stockage dans des batteries, des réservoirs de carburants synthétiques et/ou des réservoirs d'hydrogène. Dans le but de déterminer la configuration la plus rentable pour fournir de l'énergie aux petites îles, l'approche développée envisage plusieurs alternatives de transmission : (i) des câbles électriques sous-marins à courant continu, (ii) des navires spécifiques livrant soit du carburants synthétiques, soit de l'hydrogène, (iii) des pipelines d'hydrogène et (iv) des cargaisons, des conteneurs et/ou des camions citernes transportant des vecteurs d'énergie chargés sur des navires ou des ferries Roll on - Roll off existants. Trois scénarios ont été envisagés : (i) un scénario de base qui représente les systèmes énergétiques existants sur les îles, (ii) un scénario d'utilisation mixte qui n'inclut que les itinéraires de ferry existants pour la livraison de carburants synthétiques, et (iii) 100 % d'énergie renouvelable où la demande à l'horizon 2050 est satisfaite de manière durable. En outre, un nouveau critère de sélection des sites de dessalement par osmose inverse de l'eau de mer a également été développé, limitant ainsi toute production d'hydrogène vert au maximum de terres éligibles. En utilisant le Cap-Vert pour valider le modèle, les résultats montrent que l'éligibilité des terres varie de 0 à 42 % et que la pente, les zones humides et les établissements isolés sont des critères cruciaux. En outre, le scénario le plus rentable est le scénario de base, qui nécessite un investissement de 246 millions d'euros. Pour plusieurs raisons, le scénario à usage mixte multiplie l'investissement par 4, tandis que le scénario 100 % énergies renouvelables atteint la barre des 5 milliards d'euros. Parmi les sources d'énergie renouvelables, l'éolien terrestre domine nettement le photovoltaïque qui est la source la plus déployée dans tous les scénarios.

Mots-clés : Cap Vert; Énergies renouvelables ; Optimisation MILP ; Approvisionnement énergétique des îles ; Sélection des sites de dessalement.

ABSTRATO (PORTUGUESE VERSION)

Esta tese propõe uma nova abordagem para o aprovisionamento energético aplicável a todas as pequenas ilhas, incluindo os condicionalismos da água dessalinizada. Inclui a geração de energia através de energias renováveis e/ou combustível sintetizado; eletrolisador, célula de combustível e instalações de dessalinização como tecnologias de conversão, bem como o armazenamento em baterias, tanques de combustível sintetizado e/ou tanques de hidrogénio. Com o objetivo de determinar a configuração mais rentável para fornecer energia a pequenas ilhas, a abordagem desenvolvida considera várias alternativas de transmissão: (i) cabos submarinos de corrente contínua, (ii) embarcações específicas que fornecem combustíveis sintéticos ou hidrogénio, (iii) condutas de hidrogénio e (iv) carga, contentores e/ou camiões de combustível que transportam transportadores de energia carregados em navios Roll on - Roll off ou rotas de ferries existentes. Foram considerados três cenários: (i) um cenário de base que representa os sistemas energéticos existentes nas ilhas, (ii) um cenário de utilização mista que inclui apenas as rotas de ferry existentes para a entrega de combustível sintético e (iii) 100% de energias renováveis, em que a procura para 2050 é satisfeita de forma sustentável. Além disso, foi também desenvolvido um novo critério para a seleção do local de dessalinização por osmose inversa da água do mar, limitando assim qualquer produção de hidrogénio verde ao máximo de terrenos elegíveis. Utilizando Cabo Verde para validar o modelo, os resultados mostram que a elegibilidade dos terrenos varia entre 0 e 42% e que o declive, as zonas húmidas e as povoações isoladas são os critérios mais impactantes. Além disso, o cenário mais económico é o cenário de base, que requer um investimento de 246 milhões de euros. Devido a várias razões, o cenário de utilização mista aumenta o investimento por um fator de 4, enquanto o cenário de 100% de ER supera a marca dos 5 mil milhões de euros. Entre as fontes de ER, há um claro predomínio do vento em terra sobre a energia fotovoltaica, que é a fonte mais utilizada em todos os cenários.

Palavras-chave: Cabo Verde; Energias renováveis; Otimização MILP; Fornecimento de energia em ilhas; Seleção do local de dessalinização.

ACRONYMS AND ABBREVIATIONS

AC – Alternate Current

AR6 – Sixth Assessment Report

CAPEX – Capital Expenditure

CAPEX$_B$ – Base Capital Expenditure

CO_2 – Carbon Dioxide

CSP – Concentrated Solar Power

DC – Direct Current

dB – Decibel

EU – European Union

€ - Euros

€$_{2023}$ – Euros at 2023 year

GIS-MCA – Geographic Information System -Multi-Criteria Assessment

GDP – Gross Domestic Product

MW – Megawatt

m^2 – Square meter

MILP – Mix Integer Linear Programming

OFPV – Open-Field Photovoltaic

OPEX – Operational Expenditure

PV – Photovoltaic

RE – Renewable Energy(ies)

GWh – Gigawatt-hour

H_2 – Hydrogen

km – Kilometer

km^3/day - thousand cubic meters per day

kWh – kilowatt-hour

LEA – Land Eligibility Assessment

LNG – Liquified Natural Gas

LP – Linear Programming

m – meter

m^3 – Cubic Meter

m^2 – Square Meter

Max – Maximum

Min – Minimum

M€ – Million euros

RO-RO – Roll On, Roll off

SIDS – Small Islands Developing States

SSP – Shared Socioeconomic Pathways

SWRO – Seawater Reverse Osmosis

TWh – Terawatt-hour

VOR – very High-Frequency Omnidirectional Range

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Introduction

1. Contextualization & Problem Statement

Islands, viewed by many as ideal places for tourism, are also challenging geographical locations when it comes to energy systems. There are several reasons for this, including tourism itself. For example, an European Union (EU) Clean Energy for Islands report [1] states that Tilos (Greece), with a population of 500 inhabitants, has 13 000 visitors per year reaching four times the actual population during the summer peak. Such statistics suggest that their energy system should be oversized in order to handle a demand that is not guaranteed every year.

Moreover, islands are often remotely located and fossil fuel dependent which affects the three dimensions of energy security: affordability, accessibility, and availability [2]. Even the delivery of fossil fuel-based energy carriers is a difficult task. Some key challenges, in this regard, are highlighted by United Nations' report, focused on maritime transport in Small Islands Developing States (SIDS). First, small volumes make applying economies of scale difficult, often leading to high costs and longer paybacks for investments. Second, trade imbalances (ships are not fully loaded) and distance from main shipping routes, especially when fuel prices increase, further complicate the situation. Third, businesses are not static. So, if companies grow and so do cargo requirements to maintain routes, it might affect the competitiveness of small islands. Finally, port infrastructures, which lack proper equipment, also have a negative impact [3].

As important as the above-mentioned is water supply. Many islands are water-scarce regions and, being surrounded by salt water, it is only natural that desalination is to be considered as a possible solution. In fact, desalination technology is pinpointed by several authors as an alternative water supplier [4]. The drawback is that it can further stress the energy systems of islands for being energy intensive. On top of that, islands are quite sensitive to climate change with rising seawater, changes in rainfall, and extreme temperatures being significant threats [5].

Nevertheless, the rising interest in renewable energies (RE), technological advancements as well as a significant RE potential, present an opportunity for islands to take control of their energy systems. However, it is still a difficult solution to be achieved. Limited space, difficult access to new technologies, and lack of qualified labor are just a few barriers [6].

All in all, energy systems on islands are unique and therefore should be addressed carefully if the most cost-effective solution is to be found. Cost plays a crucial role in these types of energy systems; therefore, no option should be ruled out until proven otherwise. Furthermore, due to their small relevance, islands are underrepresented in existing models [7]. As such, there is still the need for an approach that incorporates such uniqueness, especially for small islands.

2. Research Questions

Research questions include:

a) What is the most cost-effective solution to deliver energy to small islands including a desalinated water constraint?
b) What is the impact of including maritime transport in energy provision for small islands?
c) What impact do additional constraints in maritime transport options have?

3. Research objective

The current study aims at proposing a new approach for energy provision applicable to all small islands including desalinated water constraints.

4. Specific objectives

The specific objectives addressed in this work include:

a) Define the crucial components of energy provision
b) Analise the existing maritime routes in Cape Verde
c) Define and compare different scenarios applied on Cape Verde
d) Assess the water generation through desalination in Cape Verde
d) impact do additional constraints in maritime transport options have?

5. Thesis structure

After an introduction which gives an overview of the context that motivates this as well as the research questions, objective and structure of the thesis, the chapter I presents the literature review of both energy systems and desalination site selection. Chapter II presents the study area and discusses the methodology applied. The results are presented in chapter III along with the respective discussions by applying the model to Cape Verde. Ending, limitations of the current work, concluding remarks as well as suggestions for future work are given.

Chapter 1: Literature Review

1. Introduction

In the present chapter, insights into how the literature is addressing both the desalination site selection and energy provision to islands are presented. The gaps found in the literature review are also presented in this section.

2. Desalination Site Selection

Seawater desalination can be defined as a process in which salts and dissolved solids are separated from seawater. Such a simple definition is what fulfills water demand in many regions of the world. Depending on the energy source, it can be categorized as a heat-driven process thus thermal technology[1] or an electricity-driven process named membrane technology[2]. Among the existing technologies, the often-used ones are multi-stage flash, multi-effect distillation, and reverse osmosis (RO), the latter being the most used representing 69% of desalination capacity in 2019 [8]. Therefore, given the increasing interest in desalination, assessing sites where facilities could be sustainably built is wise.

The conducted literature review comprised 22 studies including 19 research papers, 2 reports, and 1 book [9-30] all related to desalination site selection, of which a total of 33 criteria were identified (Table 1).

Table 1 highlights that the most frequent criteria are proximity to a water source (seawater, well, river), accessibility, and proximity to electric grids. Andrianne and Alardin [9] stated that it is much cheaper to pump and transport fresh water compared to salt water while Dawoud et al. [10], consider that being away from the sea would avoid possible destruction caused by seawater intrusion. However, no buffers were stated in these studies. Other studies including wells [11] or rivers [12] as water sources, considered that the closer the plant is to the water source, the better it is. Nevertheless, maximum distances up to 2 500 m [9 - 12] were found with some of the authors considering different ranges instead of a single value [14, 16]. Regarding accessibility, Tsiourtis [17] considers that the availability of roads in the vicinity of plants is advantageous during construction and operation as it lowers costs. However, Mahjoobi and Behzardi [12] approach it from a crisis standpoint stating that roads are crucial in such times.

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[1] As in multi-effect desalination, mechanical and thermal vapor compression, and multi-stage flash distillation.

[2] As in reverse osmosis, forward osmosis, and membrane distillation.

Table 1 – Criteria identified for desalination site selection in the literature, N represents criteria frequency

Criteria	N	Sources
Proximity to a water source (river, seawater, well)	**11**	[9 - 14], [17], [18], [21], [23], [27]
Accessibility (e.g. road networks)	**11**	[12], [14], [17], [18], [21], [23], [24], [27 - 30]
Proximity to the electric grid	**9**	[9], [14], [17], [18], [23], [27-30]
RE potential	**8**	[11], [13], [19 - 21], [26], [27], [30]
Land slope	**8**	[12 - 14], [18], [21 - 23], [26]
Water/energy price	**7**	[9], [19], [20], [23], [27], [29], [30]
Water/aquifer salinity	**7**	[11], [18 - 20], [23], [26], [30]
Distance to settlements	**7**	[9], [14], [17], [18], [23], [24], [28]
Altitude/elevation	**6**	[9], [12], [14], [21 - 23]
Water quality	**6**	[9], [10], [17], [18], [23], [30]
Conservation/protected areas	**6**	[14], [17], [18], [23], [27], [28]
Availability of water distribution networks	**6**	[9], [17], [23], [27], [29], [30]
Water demand	**5**	[9], [10], [21], [23], [27]
Land use	**5**	[12], [21], [22], [26], [30]
Water temperature	**5**	[18 - 20], [23], [30]
Local regulations	**5**	[9], [23], [27], [28], [30]
Population	**4**	[19 - 21], [27]
Technology & size to be installed	**4**	[9], [10], [13], [23]
Brine disposal	**4**	[17], [23], [27], [29]
Level of skill of the labor force	**3**	[9], [23], [27]
Proximity to consumers	**3**	[9], [23], [28]
Land available	**3**	[13], [23], [29]
Dunes/rock faults/seawater intrusion/flash floods	**3**	[11], [12], [18]
Existence of recreational sites/ cultural heritage	**2**	[16], [24]
Precipitation/rainfall	**2**	[12], [20]
Aquifer depth	**2**	[10], [11]
Agricultural areas	**1**	[24]
Estuary[3], Fetch[4], Ocean Current Velocity	**1**	[18]
Distance to contamination sources	**1**	[10]
Ambient Temperature	**1**	[26]
Availability of data for existing infrastructures	**1**	[27]
Bed slope, Drainage density	**1**	[22]
Wetland	**1**	[16]

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[3] Areas where freshwater mixes with saltwater.

[4] Areas where waves are generated by wind.

As for the proximity to electric grids, all authors agreed that being close to the electric grid or off-grid RE supplies is better given that desalination is energy-intensive and that transmission expenses would be minimized. For example, Garcia-Bartolomei et al. [14] and Gholamalifard et al. [18] both considered buffers of 100 m for roads and 200 m to supply sources.

The site's renewable energy potential, slope, and elevation are also popular criteria among authors. Control over carbon emissions has motivated RE-powered studies even in the desalination field. It can be seen, for instance, in a global analysis aimed at identifying regions for solar-aided desalination infrastructures (>5 kWh/m^2/day) [19] as well as in Ayadin and Sarptas' study [20], focused on solar desalination plants in Turkey, that held solar energy (>150 kWh/m^2/day) as one of the most important criteria. The slope is often based on the required earthwork and capital to do so [9, 12, 21]. Usual values range from 1% [13] to 15% (often split into different categories) [14, 18, 22]. Similarly to slope, elevation is considered in the sense that it can increase the energy consumption and difficulty to build desalination plants [12, 21, 23]. The only constraint found is 1 500 m, also split into different categories [14].

Furthermore, there is a concern about living standards. It is often translated into a settlement criterion. A report on the Cape Riche Seawater Desalination Plant's proposal, done by the Environmental Protection Authority of Western Australia [24], as well as Tsiourtis' study [17], highlighted that desalination plants can have negative impacts on social surroundings due to excessive noise, odor, change in landscape, aesthetic, and restriction to recreational sites. The literature buffer distances include 1 000 m [14], 1 000 and 1 200 m for villages and cities respectively [18], 1 500 m [25], and up to 4 000 m (split in different categories) [16].

The energy intensity feature of desalination plants is another aspect that is indirectly taken into account. Salinity level (e.g., around 30 parts per thousand [20]) and water temperature (e.g., around 25° [19]) are, therefore, relevant examples given that low salinity levels and high-water temperatures are preferred in several studies as they lead to lower energy consumption [26]. Just as important is the water demand criterion. For example, Banat et al. [27] use it as the reason behind building a desalination plant in the first place while Andrianne and Alardin [9] state that large demands can sustain the high price of desalinated water. No actual buffer is provided though.

The water demand criterion is further considered through the population (as an indicator of water demand [20]- a population higher than 15 million was preferred), proximity to consumers, water stress (thus the existence of water demand [19, 23]), precipitation (as an indicator of water scarcity [12, 20]), and water price (an indicator of economic demand [19] and water scarcity [20]). Still within water-wise criteria, water quality is often connected with chlorine concentration, nitrate concentration, contamination sources [10] as well as pollution (oil spillage) [9]. Additionally, sites with existing water distribution networks are advantageous as it is easier to handle the produced water [17, 27].

Table 1 also yields non-quantifiable parameters. It refers to local regulations and the participation of the community in the decision-making process. A few authors see it as a way of ensuring that the project is in line with what the government and population envision for their surroundings [17, 23, 27, 28]. Turning to protected areas, Shahabi et al. [28] and Tsiourtis [17] agreed that desalination plants should be located outside of environmentally sensitive areas. Nevertheless, other authors considered this parameter through the exclusion of conservation/protected areas. Buffer distances of 1 000 m [16], 3 000 m [14], and up to 7 000 m [18] are found in the literature.

Land availability is approached from different angles. Andrianne and Alardin [9] refer to it based on the cost of land and subsoil pollution while Banat et al. [27] consider that there should be enough space for the desalination facility, PV plant, and containers to store equipment. A similar criterion is land use with Mohamed [21] and Mahjoobi and Behzadi [12] both suggesting that empty areas are preferable as it reduces cost and saves time.

Moreover, the integrity and security of desalination plants are not neglected during site selection. To ensure that, Salim [11] excluded sites with dunes and those susceptible to floods. Earthquakes, landslides, and liquefiable sands were a concern for Sadri and Rahmani [23] as they lead to problems during construction, operation, and commissioning. He also considered oceanography to prevent marine hazards. Additionally, Mahjoobi and Behzadi [12] considered a distance from faults to reduce the vulnerability of desalination plants. Other studies also considered rock faults and seawater intrusion with Gholamalifard et al. [18] stating a buffer of 1000 m regarding faults. Further, several authors show concerns about the technology and size of the desired desalination plant, brine disposal, and skill level of the local labor force. Negative impact on surroundings, the plant’s brine production, and preference for sites with qualified labor force are pinpointed as reasons behind these criteria [9, 10, 13, 23, 27 - 29].

Less frequent criteria were aquifer depth (affects pumping cost), proximity to agricultural areas (the study aimed at desalination for irrigation), distance to contamination source (yields better water quality), and ambient temperature (decreases the efficiency of PV panels in PV-powered desalination). The same can be said for the availability of data (fully defined data-wise regions are preferred), drainage density (to avoid selecting areas vulnerable to flood) as well as the estuary, the velocity of the current, seabed slope, and fetch that represent marine zones [10, 11, 18, 22-24, 26, 27].

3. Energy Provision

The literature review concerning energy provision was mostly focused on two aspects: (i) finding out how islands are being addressed in the literature as well as how existing models consider them and (ii) understanding how fossil fuels are being delivered to islands. As an initial step, several open models were analyzed with the objective of identifying how islands are being accounted for. These models are shown in the following Table 2.

Table 2 – Open-source models reviewed

Model	Acronyms	Islands	Source
Asian-Pacific Integrated Model	AIM/Enduse	Not mentioned	[31]
Open-Source Energy Modelling System	OSeMOSYS	Not mentioned	[32]
Global Energy System Model	GENeSYS-MOD	Not mentioned	[33]
Python for Power System Analysis	PyPSA	Not mentioned	[34]
The Integrated MARKAL-EFOM System	TIMES	Not mentioned	[35]
The Prometheus Model	-	Not mentioned	[36]
Coastal Impact and Adaptation Model	CIAM	Low-lying islands were omitted	[37]

By looking at Table 2, it can be said that islands are not a crucial section when it comes to existing energy models. Such models are more concerned with bigger energy systems. In fact, Prina et al.[7], aiming at identifying which models are applied at island level and their impacts, state that models often designed for country level (TIMES, OSeMOSYS) are adapted to islands and insular applications. The mentioned authors also highlight that (i) energy systems for islands should account for seasonal variabilities due to lack of space, no economies of scale, etc.; (ii) existing studies do not directly incorporate maritime transports, which is crucial, especially in small islands; and (iii) desalination plants should be considered especially in small islands with negligible industrial sector as it represents the highest load.

Further, the absence of maritime transport was again verified by accessing other works. Marczinkowski and Barros [38] assessed 100 % RE share in the Madeira islands considering both technical and institutional aspects. Even though this paper considered the transport sector, it was limited to vehicles. The same limitation is verified by Barrera-Santana and Sioshansi [39] which presented an optimization model for long-term capacity planning of island electricity systems as well as Alves et a. [40] focused on analyzing the impacts of interconnecting the Portuguese islands of Pico and Faial.

Again in line with what Prina et al. [7] concluded, papers do not often address how fossil fuels are transported to small islands. Authors only state that islands are usually dependent on fossil fuels, as in [41], with some papers highlighting sectors that use fossil fuels the most (see [42]). However, Matutula et al.’s study [43] is an exception to that. The authors indeed took a closer look at the supply chain of fossil fuels along with the means to do so, including maritime ones. Taking the case of Lease Archipelago, the authors state that fossil fuel delivery is often done using trucks (5 000 liters) and loading/unloading drums into small boats (drums are plunged into the sea during this process). Additionally, it was stated that the process lasts 9 hours if no delays occur and that it has several problems such as limited boat capacity (5 to 6 tons), safety concerns as well as dependency on weather conditions. It was the author's opinion that optimizing shipping routes, ship size, and frequency of delivery would reduce costs thus suggesting a pusher-barge service to supply fuel oil to small islands.

Similar fossil fuel delivery means are also present in other islands as the following Table 3 reports.

Table 3 – Examples of fossil fuel delivery to islands

Islands	**Country**	**Fuel delivery method**	**Source**
Guadalcanal, New Georgia, Ghizo, etc.	Solomon Nation-State	Inter-island vessel	[44]
Outer islands		Boats	
Kiribati	Kiribati Islands	Small coastal tankers	[45]
Funati	Tuvalu Islands	Medium scale tankers	
Savaii	Samoa	Medium range tankers	[46]
Viti Levu	Fiji Islands	Medium range tankers	
Majuro	Marshall Islands	15 000 L tankers	[47]
Madagascar	Madagascar	Coastal vessels, barges	[48]
Madeira	Portugal	Container vessel	[49]
Brava, Sao Nicolau, etc.	Cape Verde	Inter-island vessel	[50]

Table 3 indirectly highlights another common trend in Islands states. It refers to fuel distribution by stages. This is the case of Cape Verde, for example. Fuel oil is delivered to the island of Sao Vicente and then further distributed to the other islands. Butane can also be mentioned as it is delivered and stored in Santiago and then distributed to the other islands [50]. Another example is found in the Cook Islands, where Fiji is considered intermediate storage. With the aim of reducing costs, fuel is delivered and stored in Fiji, and later distributed to other/outer islands such as Rarotonga [46].

4. Concluding remarks

It can be concluded that existing desalination site selection studies consider technical, economic, social, and environmental spheres as criteria and often prefer to use Geographic Information System –Multi-Criteria Analyses (GIS-MCA). Another conclusion drawn is that there are no fixed criteria for desalination site selection. Different authors considered different criteria with just a few being often used. Besides that, some studies do not provide a clear explanation behind criteria and/or buffer distances. As such, their comprehension is left to the readers thus allowing possible misunderstandings. In addition, the lack of values is disadvantageous. It leads to assumptions that ultimately yield inconsistency.

All in all, there are a number of studies in the literature addressing desalination site selection however, to our best knowledge, none assessed land eligibility for seawater reverse osmosis with a particular focus on green hydrogen production. Thus, this is one of the contributions of the current study.

Regarding energy provision, existing models do not consider islands or often disregard important features by adapting larger energy system models to island applications. Additionally, there is a tendency towards neglecting maritime transport that has an important role in island states, as shown in Table 3 and Matutula et al.'s study [43]. Furthermore, the distribution of fuel by stages is often applied in island states, most likely to reduce cost, which suggests that storage is also an important component of these systems.

Within such a scenario, the impacts of considering local maritime transports in energy provision apart from usual ones (e.g., DC/AC cables, pipelines) are still unanswered, thus being another gap addressed by the current study. Further, to the best of the author's knowledge, this is the first study that incorporates hydrogen, conditioned by desalination, in energy provision to island application.

Chapter 2: Material and methodology

1. Introduction

This chapter is also split into different sections. First, general concepts about the different terminologies used are presented in order to get readers familiar with them. Then, the case study country where insights about energy demand and RE potential are presented. A detailed description of the approach applied to the current study can be seen in the section methodology. It includes all the technologies considered, their techno-economic parameters, tools used. The following sections discuss the applied methodology regarding energy provision and land eligibility for seawater reverse osmosis desalination (SWRO).

2. General Concepts

Optimization aims at finding the best solution to a certain problem. There are three levels to it: (i) synthesis which handles the components that appear and their interconnection/layout, (ii) design which accounts for the technical characteristics, and (iii) operation which deals with the operating conditions of the system [51]. It is a concept often applied in the literature regarding energy systems with the objective of finding the least expensive solution to fulfill demands.

Linear programming (LP) and Mixed Integer Linear Programming (MILP) are both mathematical optimization techniques that aim at finding the optimal solution for a problem given a set of constraints. The difference between them is that MILP considers integer variables [52]. Such particularity is important, especially in small energy systems, as it allows better configurations to be found due to individual units being able to operate on/off [53] as well as better distribution of energy generation, and storage. Further, MILP better captures techno-economic characteristics which may have a significant impact as shown in Cebulla and Fichter's study (see [52]). For better understanding, an illustrative example is provided in Figure 1 below.

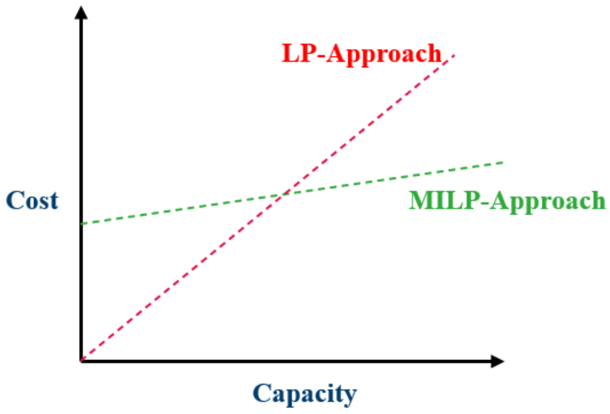

Figure 1 – LP vs MILP approach

Figure 1 highlights the dangers of applying an LP approach to small-capacity systems. The LP approach neglects the impact of initial investments (base capital expenditure) which can be significant in small systems. That can also lead to less accurate results and less flexibility. At larger systems, however, these impacts are less felt. For these reasons, in the present work, a MILP approach is applied as small islands fall in the category of small systems.

Other concepts refer to capital expenditures (CAPEX), base capital expenditure ($CAPEX_B$), and operational expenditure (OPEX). CAPEX refers to capital investments in acquiring or upgrading assets, given in euros per capacity (i.e., €/kW). $CAPEX_B$ refers to the fixed cost that has little to no dependence on capacity. For example, in the case of onshore wind turbines, $CAPEX_B$ would refer to the land leasing cost, getting the turbines to the chosen site, impact assessment studies, etc., that would most likely occur independently of the capacity. It is given in euros (€). OPEX, however, accounts for the investments that keep the asset operational throughout a certain period, often given as a percentage of CAPEX (%).

In addition, OPEX per unit refers to the cost of producing a unit of a product and is given in euros per unit (e.g., €/kWh). Furthermore, lifetime is taken as the number of years that an asset is written off, and interest rates, a discount factor to calculate annual costs, account for the temporal change in the value of money. Some of the following sub-sections report the use of linear regression which is a statistical method to model the relationship between two variables, one being dependent and the other independent.

Even though there is no clear definition of small islands as well as a clear criterion to do so, in the present study, small islands are considered as land mass with areas lower than 10 000 km^2 [54].

3. Case study

Located 455 km off the West African Coast, Cape Verde is a West African archipelago country composed of 10 islands, 9 of which are inhabited[5]. It's a small country with a total area of 4033 km^2, an annual average temperature ranging from 20 to 25 degrees, and a population of around 556 000. The islands are divided into two groups (see Figure 2) upon wind blow criteria: (i) Barlavento (meaning "from where the wind blows") composed by Santo Antao, Sao Vicente, Santa Luzia, Sao Nicolau, Sal, and Boa Vista, and (ii) Sotavento (meaning "where the wind blows away") which includes Maio, Santiago, Fogo, and Brava [55].

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[5] Santa Luzia is the only exception.

Like many other small island states, Cape Verde's energy sector is heavily dependent on fossil fuels. A report done by Electra [56], the company that manages energy and water in all inhabited islands except for Boa Vista, stated a 468.9 GWh energy production in 2022. A share of 83.2% of that energy was produced by thermal power plants that burn diesel and/or fuel oil, with wind and solar accounting for the remaining part. Furthermore, the report also highlights a 25.4% loss of energy at the country level (a concerning 34.5% on the most populated island), and several blackouts ranging from 4 to 29 in number (the smallest island, Brava, being the most vulnerable one). To complicate matters, there are no interconnections among islands, each one having its own energy grid meaning that economies of scale are difficult [57]. Regardless of having the highest energy access rate among the West African countries, 90.3% in 2018 [58], Electra's report proves that there is still room for improvement, especially in a sustainable way.

As important as the energy sector is water availability. Cape Verde has little surface water and insufficient rainfall [59]. As such, the country depends on desalination for water availability. In fact, desalinated water accounted for 99.3% of water consumption in the islands of Santiago, Sao Vicente, and Sal (in 2022), where Electra owns desalination plants with capacities of 20 000 m^3/day, 16 600 m^3/day, and 51 400 m^3/day, respectively [56].

It is a country with significant RE potential, a potential that can be verified in the H2 Atlas Tool [60]. In fact, this tool suggests a potential of 29.79 TWh/year in onshore wind and 97.06 TWh/year in OFPV, in 2020, restricted by a land eligibility of 22.34% in onshore wind and 21.32% in open-field PV (OFPV). The vast potential of Cape Verde is already recognized at a country level which is translated into the national RE targets of 50% (by 2030) and 100% (by 2050) [57, 61] as well as the RE installed capacity that is already in place.

Regarding RE, a capacity of 33.5 MW can be identified in the country [62]. Wind accounts for 26 MW while solar accounts for the remaining part. Cabeolica, the company that owns and manages large parts of the wind turbines in Cape Verde, accounts for 25.5 MW of the capacity installed in onshore wind energy. This capacity is distributed in four wind parks, with a total of 30 wind turbines, located in the islands of Sao Vicente, Santiago, Sal, and Boa Vista [63]. Electra manages the remaining share. Additionally, several projects are being planned. These projects include the expansion of wind and solar installed capacity, pump storage as well as battery energy storage [64].

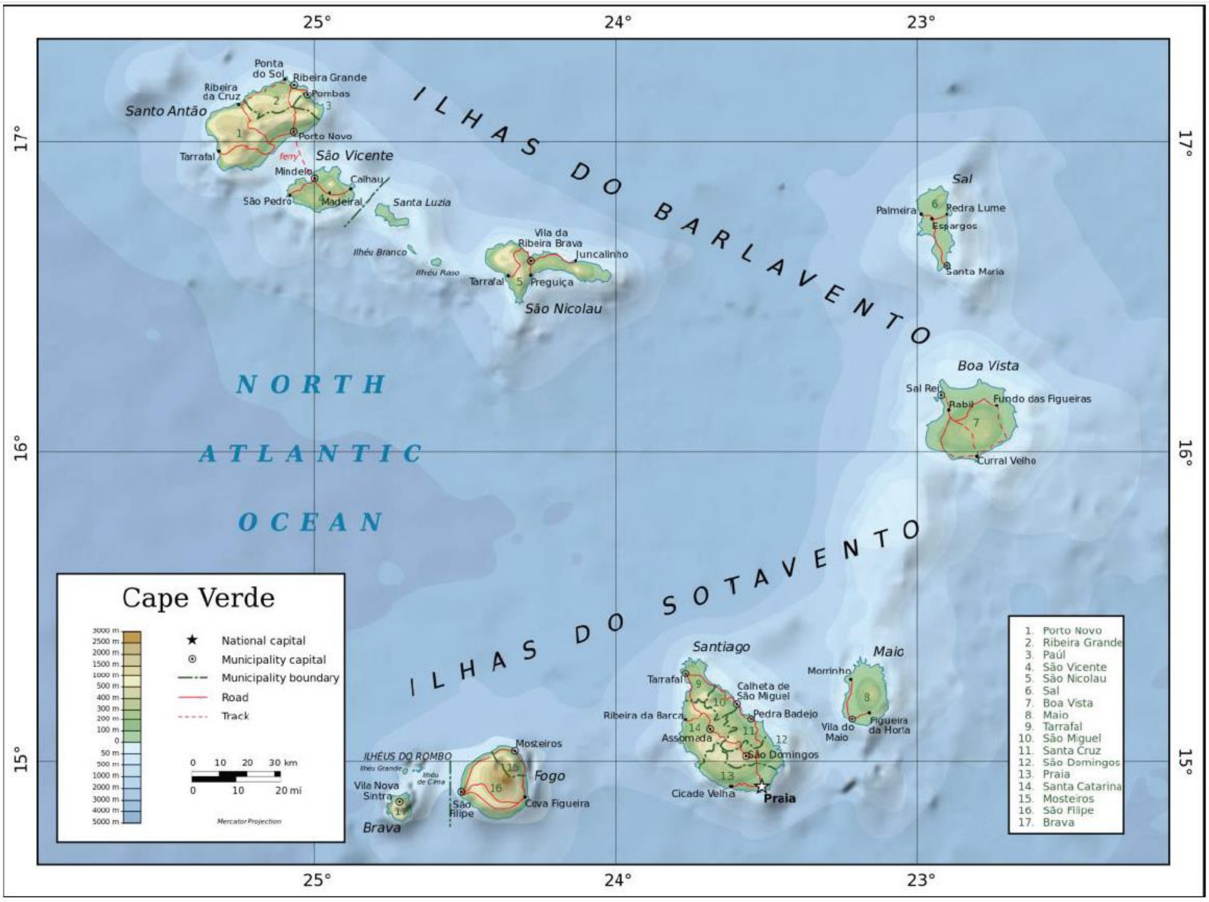

Figure 2 – The Cape Verdean islands

Source: [59]

Therefore, Cape Verde’s high electricity access rate and renewable energy potential, political will, experience, local labor, and acceptability regarding renewable energies are driving forces behind choosing this country as a case study.

3.1. Distance Matrix & Route Eligibility

The eligibility matrix basically states the routes that are allowed to a certain transmission technology. All the transmission technologies are distance dependent. Therefore, the distances between the different islands, as well as the eligible routes, should be provided. In the current study, the distances were obtained from [65], which refers to the distances between the main ports of each island. In the case of vessels as transmission technologies, all routes are considered eligible.

These distances, shown in the following Table 4, were considered for all transmission technologies provided that such routes are eligible.

Table 4 – Distance matrix (km)

INDEX	Santo Antao	Sao Vicente	Sao Nicolau	Sal	Boa Vista	Maio	Santiago	Fogo	Brava
Santo Antao	N/A	14.816	88.896	224.092	262.984	296.32	281.504	246.316	242.612
Sao Vicente	14.816	N/A	81.488	220.388	240.76	285.208	296.32	240.76	240.76
Sao Nicolau	88.896	81.488	N/A	159.272	162.976	203.72	220.388	170.384	192.608
Sal	224.092	220.388	159.272	N/A	68.524	183.348	214.832	266.688	275.948
Boa Vista	262.984	240.76	162.976	68.524	N/A	124.084	153.716	224.092	233.352
Maio	296.32	285.208	203.72	183.348	124.084	N/A	38.892	133.344	148.16
Santiago	281.504	296.32	220.388	214.832	153.716	38.892	N/A	112.972	127.788
Fogo	246.316	240.76	170.384	266.688	224.092	133.344	112.972	N/A	18.52
Brava	242.612	240.76	192.608	275.948	233.352	148.16	127.788	18.52	N/A

Source: [65]

Pipelines and subsea power cables, however, have additional constraints particularly related to the depth of the ocean. For pipelines, any route that involves a depth higher than 5 000 m was excluded while for subsea power cables, the threshold was set at depths of 3 000 m (see the transmission technologies section). To apply such constraints, Ancochea et al.[66] study was considered. It provides bathymetry maps for Cape Verde. Hence, by comparing the max depth lines displayed in these maps with the constraints set, eligible routes and ineligible ones were defined.

3.2. Route Capacity Constraints

Part of the methodology applied in the current work relies on existing ship routes. Therefore, apart from the different distances, the maximum capacity that is allowed should be stated for the cargo, fuel truck, and container transmission options. In the case of Cape Verde, the existing routes and frequency were based on the following Figure 3.

Along with the specifications in the transmission sub-section, these existing routes and respective frequencies allow new constraints given that not all the space in an RO-RO (roll on/roll off) ship, for example, is supposed to be used for energy provision (See appendix 7 for eligibility matrixes).

Information gathered suggested the maximum number of vehicles for each ship. When not specified, a total of 4 cars was considered to be the equivalent of a fuel truck. Additionally, the inclusion of containers was only allowed between Sao Vicente (with the best port infrastructure) and Santiago (the port of Praia is in the Capital of the country) given that these islands have infrastructures to handle containers [67,68]. It considers 8 trips per month, 4 containers in each trip. As for cargo, it was considered a maximum of 15 units per trip.

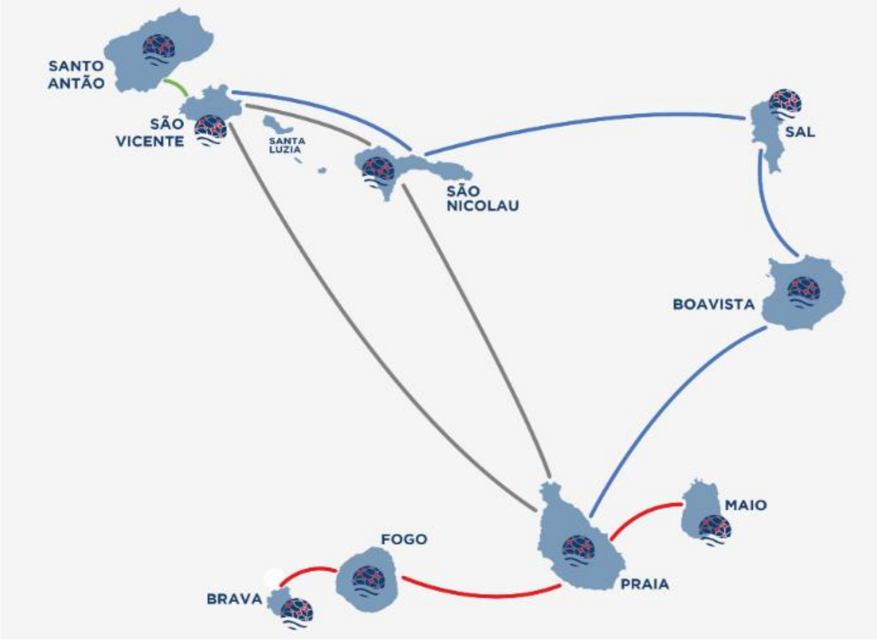

Figure 3 – Existing shipping routes in Cape Verde

Frequency: Green: 14 times per week; Blue: 2 times per week; Red: 3 times per week; Gray: 1 time every 15 days [67].

3.3. Energy demand: data for Cape Verde

Since the current study assesses a general approach to islands, global data is required. The data was obtained from [69] which estimated the global energy consumption for 2020 and 2050. For 2020's demand, their methodology involved the disaggregation of sectors (industry, agriculture, residential, transport, and service). Linear regression was also applied for missing values, often the case of small islands.

Regarding 2050's demand, a downscaling approach was applied along with the Net Zero 2050 Scenario. It considered both long- and short-term trends. The 2050 values were then obtained by the product between 2020 values and the ratio of 2050 and 2020 values. This global dataset suggests an average change of 4.635 in demand for island states. With demand from the IPCC report and applying the same scenario previously described a hydrogen demand for 2050 is also estimated.

Based on this global dataset, the demands concerning the case study country are presented in the following Table 5 as Demand_2020 and Demand_2050. Additionally, the real demand in 2022, obtained from Electra's annual report [56] is also shown in Table 5. The latest was used to validate the demand estimation for Cape Verde.

Even though this global dataset is quite accurate for large countries, some inaccuracies could be seen in the case of Cape Verde. First, the 2020 estimation tends to underestimate the energy consumption on the different islands. Considering Boa Vista as an example, it can be seen that the real demand in 2022 is far greater than both 2020 and 2050 estimations. Given that Sal and Boa Vista are important islands for tourism and thus equipped with several hotels, for example, one would expect these islands to have higher demands as shown in 2022 demands. These changes are most likely caused by the proxies used in the global estimation, particularly the population proxy.

Table 5 – Electricity demand for 2020 & 2050 (GWh)

Region	**Demand_2020**	**Real_Demand 2022**	**Demand_2050**	**Demand_2050 (based on 2022 values)**
Santo Antao	12.772	18.467	63.621	85.596
Sao Vicente	115.829	85.837	577.002	397.857
Sao Nicolau	2.294	7.486	11.428	34.698
Sal	16.846	73.698	32.811	341.590
Boa Vista	6.586	73.698	6.170	341.590
Maio	1.238	4.053	83.919	18.787
Santiago	157.933	260.174	793.689	1 205.911
Fogo	8.771	16.105	43.692	74.645
Brava	0.729	3.115	3.633	14.437
Cape Verde	**314.229**	**468.937**	**1 615.966**	**2 173.521**

Cape Verde has a heavy dependence on tourism, and tourists are not considered part of the population. This might be the reason why islands such as Sal and Boa Vista got lower demands. Underestimations also extend to other islands such as Santo Antao and Brava. Islands with the highest population (Santiago, Sao Vicente) are the most consuming ones which is in line with 2022 real demand. Nevertheless, such inaccuracies account for approximately 154 GWh which is significant, especially in the context of small island states.

The hydrogen demand estimation from the global dataset, however, is considered. Given that there is no current demand for hydrogen in Cape Verde, it is considered that the estimated hydrogen demand is a possible future demand. Additionally, it can be seen in the following Table 6 that the most significant demand is in Santiago, the biggest island in terms of size and population as well as a developed industrial sector, which adds some credibility to it.

Table 6 – Hydrogen demand (GWh)

Region	Hydrogen demand_2050
Santo Antao	10.951
Sao Vicente	0.738
Sao Nicolau	0.529
Sal	0
Boa Vista	4.258
Maio	0.327
Santiago	81.521
Fogo	9.773
Brava	0
Cape Verde	**108.098**

Source: Derived from data available in [69]

The differences between the different demands are better seen in the following Figure 4.

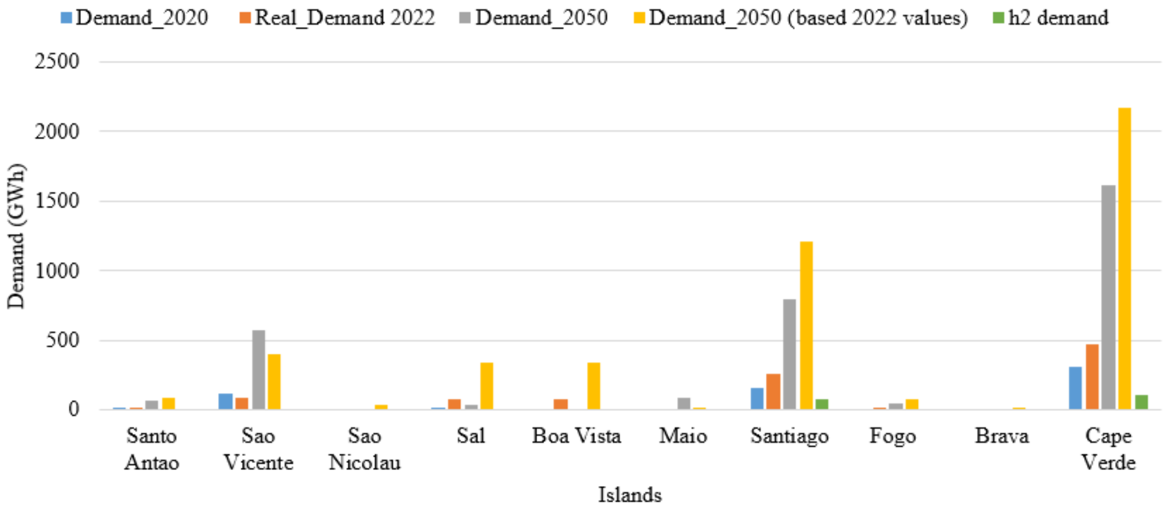

Figure 4 – Energy demand for 2020, 2022 & 2050 for the different islands

Given the inaccuracies discussed, the author opted for the real demand data for 2022 while the average change in island states, 4.635 suggested by the global dataset, was used to determine the 2050 demand. It should be noted that the island of Boa Vista is not part of Electra's jurisdiction and thus absent from the 2022 report. Due to the lack of credible sources for Boa Vista's 2022 demand, it was considered that it has the same demand as Sal given the similarities in tourism. Additionally, the time series of the PLEXOS-World Model [70] was adapted to Cape Verde's 2022 and 2050 demand in order to get demand curves out of annual demands, based on locational economy, technical and climate characteristics. Demand curves highlight seasonal variations in demand which may have a direct impact on storage, thus better than constant demands. The hydrogen demand is considered without any modifications as it refers to industrial demand which is likely to be constant.

3.4. Renewable energy's potential

As previously mentioned, the RE sources considered are wind and solar. The source of the RE potential considered in this study is Winkler's study [71]. It is a study in line with the H_2Atlas project that assessed green hydrogen production from renewable energy sources in the West and Southern African regions. Land eligibility assessments, RE potential from Global Solar Atlas, and Global Wind Atlas as primary sources, and the use of Python packages such as GLAES, FINE as well as RESkit are just a few details of the project. Much more regarding the later can be found in [60].

The RE potential data considered were, therefore, obtained from the internal database of IEK- 3, which is part of Jülich Forschungszentrum, one of the partners in the H_2Atlas project, as the author of the current study was given access to such data.

The maximum, and minimum energy output from both PV and Onshore wind turbines for the Cape Verdean islands as well as the mean energy output, in a country, are shown in Figure 5.

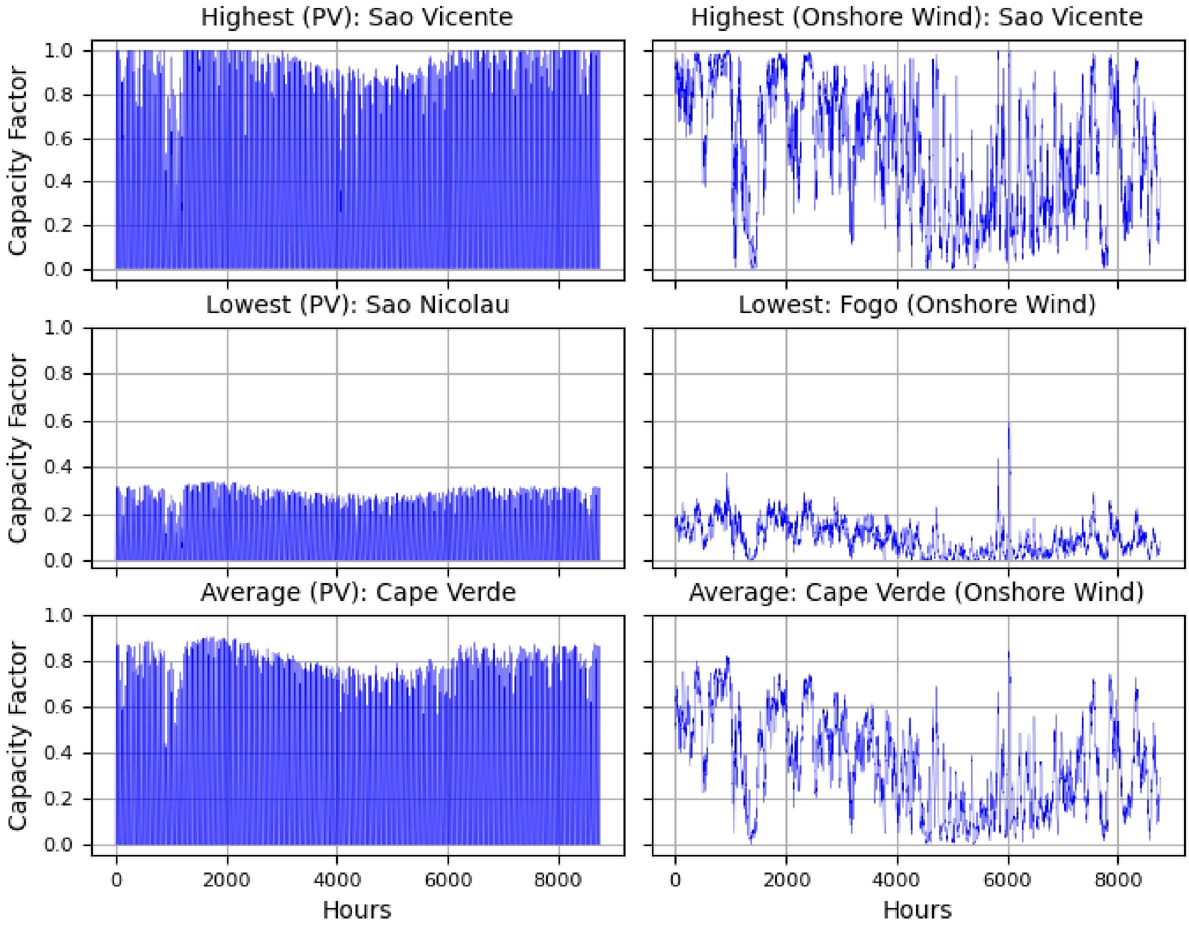

Figure 5 – PV and onshore wind capacity factor maximum, minimum, and average factor in Cape Verde

4. General Methodology

An overview of the whole approach applied in the current study is shown in the following Figure 6. It can be observed that the whole approach assumes that there is an island X with excess energy (source) and an island Y with a deficit of energy (sink). Therefore, power can flow from source to sink through six alternatives, two in the form of electricity and synfuels and four in the form of hydrogen. The hydrogen alternatives require energy to be converted into hydrogen using water strictly produced by the desalination plant. In no order, the first alternative is a direct connection between the two islands (source and sink) through a subsea power cable carrying electricity. The second alternative refers to a specific hydrogen vessel delivering energy carriers while the third and fourth ones make use of existing routes (e.g., Ro-Ro ships, ferries) to deliver energy carriers either as cargo (e.g., container) or through fuel trucks. The last alternative would be connecting islands through an offshore pipeline. Once hydrogen is delivered to the sink island, it can be either used as hydrogen, if a hydrogen demand is stated, or converted back to electricity by a fuel cell. The current approach also considers synfuel power plants that would convert synfuels into electricity, later delivered to the grid. The synfuel is assumed to be imported and stored on a specific island (intermediate storage) and then distributed to other islands. This distribution should make use of existing routes as well.

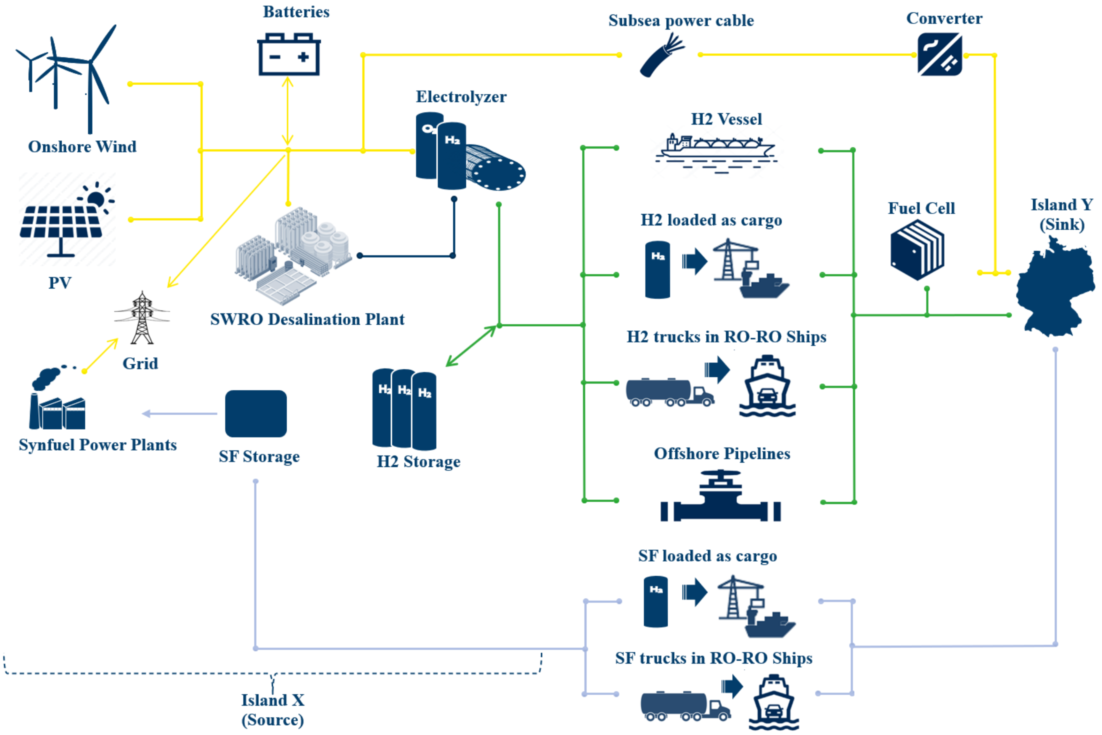

Figure 6 – Graphical Abstract

Legend: Yellow – electricity; Green – hydrogen (H_2); Blue – Synfuels (SF)

The general components can be categorized into four groups: (i) generation, (ii) storage, (iii) transmission, and (iv) conversion. More details about each step/component shown in Figure 6 are presented in in the following section.

5. Energy Provision Approach

5.1. Optimization Tool

The MILP approach developed in the current study uses an open-source Python framework entitled FINE (Framework for Integrated Energy Systems Assessment). It aims at modeling, optimizing, and assessing energy systems, even those with multiple regions, commodities, and time steps. Its objective function is to minimize the total annual cost (TAC) considering technical and environmental constraints (see appendix for more details). Much more about FINE as well as the package itself can be accessed at [72]. This package requires different components as input data such as the technologies and their techno-economic parameters, demand data, and renewable energy potential. LEA results can also be processed. These different input parameters considered in the current work, except for the ones in the case study section, are discussed in detail in the following sub-section. It is worth mentioning that all costs that were not in the 2023 year were brought to the 2023 year by online platforms that take into consideration real inflation [73,74] and that an interest rate of 8% is applied to all technologies. Units conversion as well as heating values for synfuels were obtained from [74].

5.2. Energy generation technologies

The chosen energy generation technologies are onshore wind turbines, PV, and synfuel power plants. Reasons behind such choices include their global usage and high maturity level as well as for being the technologies already in place in several island states. The latter reason indirectly pinpoints that there is potential and acceptability (for the case of Wind and PV) as well as local knowledge regarding the chosen electricity generation technologies which strengthens the applied criteria. In the case of synfuel power plants, it is assumed that such power plants can run on synfuels without further modifications. However, due to the lack of MILP techno-economic parameters in the literature, oil power plants are used as a proxy for synfuel power plants.

The techno-economic parameters concerning the RE technologies were obtained using a combination of the IEK-3 database and literature review. For the synfuel power plant, however, linear regression was used. The International Energy Agency’s 2020 report [76] provided the cost per capacity and net capacities of several oil power plants (used as a proxy) around the world upon which linear regression was applied to get a base CAPEX and MILP CAPEX (see Appendix 1 for the whole procedure). The cost of running the plant (OPEX/unit) is considered to be the fuel cost purchase, obtained from European Energy Exchange (EEX) natural gas market data [77] while the remaining parameters were also obtained from the IEK-3 database and literature review combination. The final values are summarized in Table 7.

Table 7 – Techno-economic parameters of the energy generation technologies

Techno-economic parameters		**Unit**	**Wind Turbines**	**PV**	**Synfuel Power Plant**
MILP	$CAPEX_B$	$€_{2023}$	121 665	1 293	156 925 761
	CAPEX	$€_{2023}$/kW	1 217	1 445	764 731
LP	CAPEX	$€_{2023}$/kW	1 451	776	900 000
OPEX		%	2.5	1.7	13
OPEX/Unit		$€_{2023}$/kWh	0	0	0.034
Lifetime		Years	20	20	40
efficiency		%	-	-	42

Source: Derived from [78-83]

5.3. Storage Technologies

In the present study, storage technologies include batteries, synfuel storage, and hydrogen gaseous storage. Thus, energy can be stored in the form of electricity, synfuels, and hydrogen depending on the cost-effectiveness of both alternatives.

The techno-economic parameters of the storage alternatives are shown in Table 8.

Table 8 – Techno-economic parameters of storage technologies

Techno-economic parameters		**Unit**	**Batteries**	**H2 storage (Gas)**	**Synfuels Storage**
MILP	$CAPEX_B$	$€_{2023}$	0	0	0
	CAPEX	$€_{2023}$/kWh	365	19.47	0.087
LP	CAPEX	$€_{2023}$/kWh	350	19.47	0.087
OPEX		%	2.5	2	2
OPEX/Unit		$€_{2023}$/kWh	0	0	0
Lifetime		Years	15	30	20
Efficiency (charge and discharge)		%	95	98	100

Source: Derived from [78,80, 86, 87]

Similarly to the energy generation technologies, techno-economic parameters were obtained from a combination of the IEK-3 database and literature review. Regarding hydrogen storage, no base capex was found in the literature, thus, to assure consistency and avoid forcing FINE to choose the alternative without base cost, no base capex was applied to both storage alternatives. This is also in line with what Kannengießer et al. [78] applied in their study. As for synfuels, the techno- economic parameters were compiled from [78,84, 85].

5.4. Transmission technologies

Three different transmission technologies were considered and accounted for all commodities. Since the domain of this study is energy exchange among islands, only sea-related options were considered. First, the sub-sea power cables option as it enables the interconnection of islands and the transmission of power in the form of electricity. Islands are modeled as so-called "copper plates" where internal energy flows are modeled at no cost or losses. Second, the offshore hydrogen pipeline option where hydrogen would be transmitted from one island to another via offshore pipelines. Apart from hydrogen-based ones, these are well-known technologies applied all around the world. The last option, vessels, involves two possibilities: (i) make use of local existing vessels to carry fuel trucks, cargo, and/or containers from one island to another and (ii) have a specific vessel that delivers energy carriers. These are less frequent options found in the literature and, to the best of the author's knowledge, the current study is the first one to apply it in the way described previously and in an island context. Nevertheless, Amone-Domenech et al. [88] compared the transport of green hydrogen at sea considering submarine pipelines as well as compressed and liquefied transport by ship, which have some similarities with the current study. For SF, ferries options or specific vessel are used.

It should be noted that, apart from the techno-economic parameters stated so far, additional constraints are required for transmission technologies. It refers to the cases of maximum depth and length for offshore pipelines and subsea power cables as well as the minimum depth for vessels. Regarding offshore pipelines, the techno-economic parameters were obtained from unpublish work from IEK-3 members, which applied linear regression on data available at [89, 90].

The base capex for DC cables was obtained using linear regression using total cost and length data from Liun et al. and Lauria et al.'s studies [91, 92] (the whole process is described in Appendix 2). Note that, due to the lack of data, the base CAPEX, which relates to the project development costs as well as the converters, was derived based on a reference capacity. In doing so, inaccuracies are unavoidable given that these costs vary from project to project. Therefore, it is likely that the results are overestimated and thus, a limitation of the applied approach. The remaining parameters concerning the subsea cables were also obtained from IEK-3 members'' unpublished work.

The cost parameters for the vessel were also obtained using linear regression. Vessels with different capacities and respective costs were compiled from an Asia-Pacific Economic Cooperation report on small-scale liquified natural gas carriers [93] and Fikri's study that also addressed liquified natural gas carriers [94]. Despite some similarities between both gases, hydrogen requires much higher pressures/lower temperatures. Therefore, to the techno-economic parameters derived from LNG infrastructures and used as a proxy for hydrogen ones, a factor of 2 was applied based on Ishimoto et al. [95] and Bridge [96]. Given that small islands fall in the category of small scale, only vessels with a capacity lower than 30 000 m^3 (again suggested by the report previously mentioned) were considered. Such an approach yielded a CAPEX$_B$, MILP CAPEX, and LP CAPEX. The other parameters were obtained from the Asia-Pacific Economic Cooperation report. See Appendix 3 for more info regarding the vessels' parameters.

Table 9 – Techno-economic parameters of the new transmission technologies

Techno-economic parameters		**Unit**	**Offshore Pipeline**	**Subsea Power Cable (DC)**	**Vessels**
MILP	CAPEX$_B$	€$_{2023}$	2 563 427	245 552 870	23 510 000
	CAPEX	€$_{2023}$/kW*Km	0.22	1.35	2 264*
LP	CAPEX	€$_{2023}$/kW*Km	0.49	1.35	3 295*
OPEX		%	0.9	3.5	3.5
OPEX/Unit		€$_{2023}$/kWh	0	0	0
Lifetime		Years	40	40	40
Losses		% / km	0	0.0035	0

Source: Derived from [89-96] (*vessel CAPEX is in €$_{2023}$/m^3)

The vessel transmission alternative also involves using existing routes to deliver energy. Therefore, techno-economic parameters concerning cargo (representing drums), fuel trucks, and containers are also required. All considered values are displayed in the following Table 10.

Table 10 – Techno-economic parameters of transmission technologies based on existing routes

Type	**Unit Capacity**	**OPEX/unit**	**CAPEX**
Cargo	0.2 m^3	43 €$_{2023}$/ m^3	23 €$_{2023}$/unit
LNG ISO Container 20'	20.37 m^3	896 €$_{2023}$/container	18 029 €$_{2023}$/unit
LNG ISO Container 40'	43.5 m^3	1 447 €$_{2023}$/container	38 501/unit
Fuel truck (Carries 20' Container)	20.37 m^3	326 €$_{2023}$/vehicles	338 000/vehicle H_2

Source: Derived from [97-100]

Most islands already have fossil fuel-based energy systems which are assumed to be compatible with synfuels. This means that only OPEX/unit is required for synfuel-based transmission options. In that regard, the average of several costs in different islands was applied in the current study (see Appendix 4, 5, and 6 for more details) as Table 10 reports. For the hydrogen commodity, however, acquiring the different equipment represents an extra cost that should be included. For example, Shirazi et al. [97] state a cost of 169 000 euros for an LNG fuel truck which, in the current work, was used as a proxy for a hydrogen fuel truck applying a factor of 2. The fuel truck alternative, for both hydrogen and synfuels, is assumed to be similar to the ones used by Gaslink company in Portugal. Such fuel trucks are not bonded to the containers which adds flexibility as the transmission alternative fuel truck can easily be changed to a container if desired. LNG ISO container specifications were obtained from Chart Industry [98], the same capacities being considered for hydrogen containers. The US Department of Energy 2020's preliminary results suggest a cost of 40 000 dollars (38 501 €$_{2023}$) for a 40' hydrogen storage trailer which was also applied in the current work [99]. Assuming that the cost changes linearly, 18 029 €$_{2023}$ would be expected for a 20' container while selling online platforms suggests costs of 23 euros for drums [100], as shown in Table 10. The maximum capacity allowed depends on the case study thus being required prior to any calculation. Such constraint, if applicable, accounts for the maximum number of fuel trucks and/or containers allowed in existing shipping routes as it is likely that other types of products are being transported as well.

5.5. Conversion technologies

Since more than one commodity is being considered there's a need for conversion technologies. Such is the case of (i) PEM (Polymer Electrolyte Membrane) electrolyzers that have electricity and water as input, and hydrogen as output hydrogen; (ii) PEM fuel cells that convert hydrogen into electricity; and (iii) SWRO desalination plants that consume electricity to generate fresh water out of seawater. Once again, the techno-economic parameters for the electrolyzer and fuel cell were based on the IEK-3 database as well as different papers. However, the techno-economic parameters of SWRO desalination were based on the master thesis of Castros [101]. He focused on the techno-economic assessment of water infrastructure components for global water-energy system models being these techno-economic parameters themselves an outcome of Castros' work.

The following Table 11 reports the techno-economic parameters taken into consideration.

Table 11 – Techno-economic parameters of the conversion technologies

Techno-economic parameters		Unit	Electrolyzer	Fuel Cell	Desalination Plant
MILP	CAPEX$_B$	€$_{2023}$	2 163	2 163	10 222 377
	CAPEX	€$_{2023}$/kW	933*	1 210	1 509**
LP	CAPEX	€$_{2023}$/kW	933*	1 461	1 536**
OPEX		%	3	2	6
OPEX/Unit		€$_{2023}$/kWh	0	0	0.6
Lifetime		Years	10	15	20
efficiency		%	70	55	98

Source: Derived from [79,80, ,101-104] (* compressor included **SWRO CAPEX is in €$_{2023}$/m^3)

6. Land Eligibility for SWRO desalination plants

6.1. Land Eligibility Assessment tool

The present assessment is done using the open-source Python package GLAES (Geospatial Land Availability for Energy Systems) embedded in the Global Energy Potential tool (GlobEP). GLAES is a framework that conducts land eligibility analysis in a standardized way, with a high degree of flexibility, and is applicable in any geographical region at any resolution [105]. Once input parameters are provided (e.g., dataset of exclusions, buffer distances) GLAES can provide relevant information regarding the available land areas as well as the maximum installable capacity by using an item distribution feature. GlobEP, however, is a tool that uses GLAES and includes several global datasets. Sources and datasets include Open Street Map, RAMSAR, World conservation Monitoring Centre, elevation datasets. Each exclusion criterion is computed individually, the final land eligibility value being obtained by the overlap of all the exclusion criteria.

6.2. Exclusion criteria methodology

By applying a general approach to desalination site selection, eligible areas are identified and, along with the plant's capacity and respective footprint, it ultimately leads to a maximum quantity of water that can be produced. It should be noted, however, that the present assessment represents a rough estimation given that precise results would only be obtained with a bottom-up approach. It would require involving the local communities in the decision-making process, site-specific regulations (that may differ from one site to another) as well as impact assessments, to name a few. Such particularities are hard to be incorporated in a general approach, thus pinpointed as a limitation of this work.

Nonetheless, the different steps adopted in the land eligibility assessment are summarized in the following Figure 7. These steps are further explained in the following subsections.

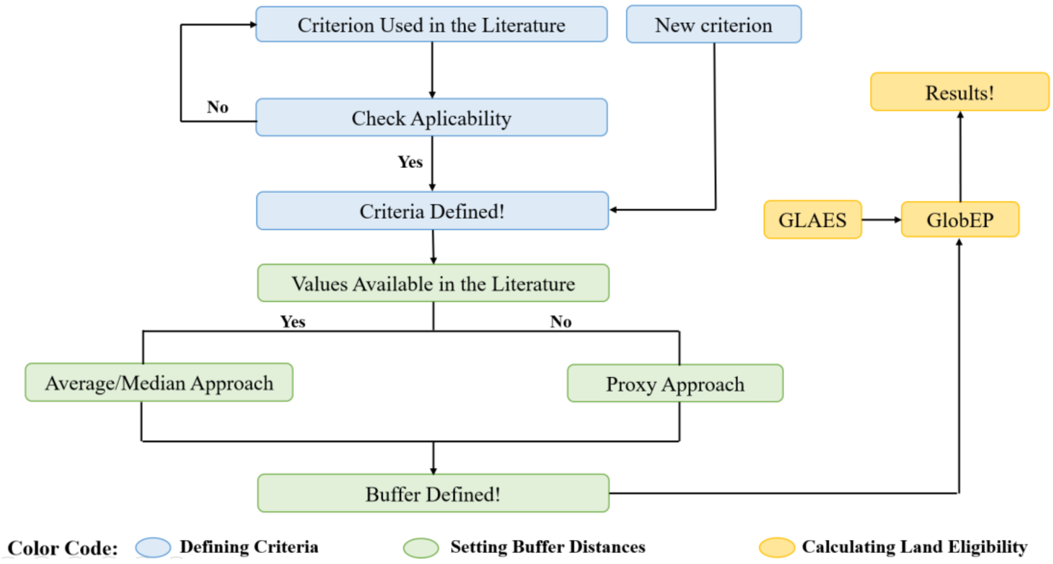

Figure 7 – Methodology for the SWRO land eligibility assessment

The literature review showed that existing studies consider technical, economic, social, and environmental parameters as criteria. While it is true that they are relevant to desalination site selection, the approach to be applied in the current work differs from the existing ones in several aspects. Land eligibility is determined through GlobEP-GLAES by using a binary approach. Different from GIS-MCA, often used in literature and that can consider multiple conflicting criteria to rank sites, the binary approach aims at differentiating eligible sites from ineligible ones.

Furthermore, the desalination section is only part of a broader scope, energy provision, given the output of GLAES, is to be further processed by the FINE framework. In other words, the water produced is intended for hydrogen production. This particularity is important because criteria such as proximity to consumers, population, and water pipelines, considered in the literature, are of less importance. Water demand is bonded to hydrogen production, thus proximity to exiting water pipelines is not a crucial factor as the desalination plant might be in the vicinity of a hydrogen production facility. Further, proximity to cities as well as water prices were used by different authors with the intuition of narrowing sites that can afford desalinated water prices. Such an argument is not applicable in the current assessment as desalinated water's impact on hydrogen production is less than 1% [106]. Similarly, proximity to the electrical grid and energy price is of low relevance when on-site renewable energy production is a possibility.

Renewable energy potential criteria are considered in the FINE framework, therefore absent from this initial step.

Likewise, labor force, accessibility, and water quality, including salinity level and temperature, were not considered. These criteria do not impose restrictions on building desalination plants. They would rather make it more costly and thus not compatible with this assessment. Other exclusions are local regulations, budget/timing, availability of data (for not being quantifiable and/or applicable to this work), land use (difficult to be applied as RO is very scalable), technology, and size (as it is already defined), brine disposal (assumed to be disposed of in the ocean thus being accounted in distance to the shoreline criterion), ambient temperature (not relevant to desalination plants) as well as an estuary, current velocity, and fetch (sensible zones are accounted in marine protected areas).

Based on the above discussion, a new approach was adopted by considering a new set of exclusions. These exclusions are divided into three categories: Physical, sociopolitical, and nature conservation areas. Moreover, as stated in the literature review section, there are few buffer distance values in existing studies. This issue is addressed in this study by considering other non-desalination-related studies that are relevant to the topic. For instance, Winkler's study [70], concerning open-field PV (OFPV), is of particular interest as similarities between both SWRO desalination and OFPV site selection criteria exist. For example, neither has a significant visual impact. Nonetheless, the details and reasoning behind each criterion are presented as follows.

a) Physical category

The physical category, on the one hand, refers to the sites where building a desalination plant would compromise the infrastructure. It involves exclusions such as mining sites, wetlands, dunes, rock faults, and flood areas. On the other hand, physical limitations that heavily impact the cost of building a desalination plant are considered. It refers to sites with high slopes and/or elevation, requiring more earthworks and/or pumping work.

It is not advisable to build over dunes as once exposed to the wind, dunes are vulnerable to erosion thus threatening the foundations of infrastructures. Similarly, mining and rock faults sites represent an instability risk to any infrastructure. Therefore, apart from being excluded, a buffer distance of 100 m (based on [70]) is applied to such regions. Further, areas that are vulnerable to flooding are also risky zones due to destruction concerns. Hence, any zone susceptible to flood in 100 years was excluded with no buffer (given the large time range).

Even though water bodies, to a minor extent, may involve stability concerns, this exclusion mainly addresses the spillage risk as (i) the high salinity level of brine would endanger marine life and (ii) water bodies would be polluted with chemicals. Only a single buffer was found in the literature, 400 m [18]. However, a study focused on locating sites for industries in Bangladesh was also considered due to the industrial character that some desalination plants have. Such a study, with a similar reasoning as the one considered, applied a buffer of 500 m [107]. Given that the magnitude of the values is similar, a buffer of 400 m was chosen to water bodies.

Other criteria are borders, glaciers, and wetlands. Borders represent zones susceptible to conflicts over boundaries thus excluded with no buffer. As for glaciers, falling ice and glacier-related floods are some of the hazards that can be pinpointed. Also, building over permafrost[6] would compromise the foundation of any infrastructure, especially in the context of climate change. Such reasons motivated a buffer of 1 000 m, also based on OFPV [70]. Wetland is a rare criterion in literature. Sepehr et al. [16] were the only authors stating a buffer to this criterion while assessing desalination site selection in Southern Iran. He considered buffers ranging from 1 000 to values higher than 4 000 m in different categories. However, no reasoning behind this criterion/buffer distance was stated. Therefore, due to the lack of values and credibility in the value found, the exclusion wetland is considered in this study as soil covered by water to which a buffer of 100 m (stability concerns – like dunes, and mines) is applied.

As stated in the literature review, slope values between 1% and 15° were found. Gastli et al.'s [13] value (1%) was disregarded as the objective of the study was site selection combining desalination plants with CSP technology. Since the chosen technology is RO and knowing that CSP technologies strictly require flat lands, this slope was not considered. Other authors either set higher constraints such as 15% (around 9°) [18], 15° [14] or did not consider constraints allowing values higher than 45% (around 24°) [22]. However, in the latter three studies, instead of choosing a single value, authors rather split the slope into categories. For instance, Garcia-Bartolomei et al. [14] considered the categories (i) very high (0-3°); (ii) high (3°-5°); (iii) medium (5°-8°); (iv) low (8°-12°) and (v) very low (12°-15°). Given that similar categories were applied in the other studies, the class medium was deemed acceptable in the current study.

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[6] Permafrost – any ground that remains frozen for more than 2 years.

Taking the upper limit of all medium classes (8°, 9°, 15° and 17°) leads to average and median values of 12.25° and 12°, respectively. Based on that, a slope of 12° was chosen.

Note that, despite not considering a slope higher than 12°, it does not mean that it is impossible to build a desalination plant under such conditions. It would only require larger amounts of capital. This might be one of the reasons why no constraints were considered by Radwan et al. [22]. Additionally, no unique slope value dictates if a land is eligible or not. The slope is a criterion strongly related to economic decisions and the author's judgment thus a difficult criterion to be determined.

The elevation criterion is also strongly dependent on economic decisions. As it affects the energy consumption of pumps, an important component of desalination plants, extreme values of elevation should be avoided. Garcia-Bartolomei [14] set a constraint of 1500 m above sea level meaning that elevation higher than 1 500 m would be excluded. Different categories were considered by him with elevations lower than 300 m being ideal. Due to the lack of other values, the maximum elevation is assumed to be limited by the energy consumption of the pump. It is considered that a maximum of 3 kWh of energy consumption is allowed for the pump (the same energy required by a medium-scale desalination plant). With this consumption, an altitude of around 1 000 m (2.725 kWh/m^3 raising water to 1 000 m [108]) can be reached thus being the constraint considered.

A minimum elevation was also set. It is a constraint that takes into account sea level rise. The relevance of it is that, depending on future emission scenarios, (i) part of the coastal area may be lost to seawater intrusion and (ii) seawater-land boundaries may be disturbed which would affect minimal distance to the shoreline. Several studies suggest seawater level increases around 1 m, by the end of 2100, especially when the worst-case scenario is considered [109]. In fact, according to the IPCC AR6 report, sea level rise might reach 1.02 m under the shared socio-economic pathway – SSP5 – 8.5 [110]. Despite the low confidence levels of it, a conservative approach is taken by assuming a sea level rise of 1 m. In addition to that, it is unlikely that any infrastructure would be built at sea level (0 m) thus another 1 m is considered. This yields a minimum elevation of 2 m. Any value below it is excluded.

As previously stated, sites near the shoreline are preferable as lower expenditures are achieved. However, shorelines can also be seen as risky zones due to corrosion, the existence of dunes, and vulnerability to seawater hazards. These aspects are deemed important and, therefore, considered through a minimum and maximum distance to the shoreline. The minimum distance to shoreline criterion is absent from the literature, however, a study that addressed the role of coastal setback regarding coastal erosion and climate change [111], states that on average 100 m is kept between the shoreline and constructions. This value is also in line with what Winkler [70] considers regarding OFPV. Thus, a minimum distance of 100 m is considered. A different situation is verified regarding a maximum distance. The literature review yielded values from 300 and 500 m to 2 500 m (in intervals of 500 m) [13-16] as buffer distances. Additionally, Jones et al. [112], assessing the state of desalination and brine production, stated that 80% of global brine production is located within 10 000 m of the Coastline. This distance is also considered as brine is assumed to be disposed of in the ocean. A median and average of 1 500 m and 2 500 m was then calculated. Similarly to slope and elevation, this parameter is also dependent on economic decisions. Even though the average is affected by the extreme value of 10 000 m, thus quite different from the median, it is still considered in this study. The reason refers to an important difference between the maximum distance to the coastline and the slope. While the slope parameter might enable a whole island to be eligible, depending on its geographical characteristics, the same does not happen with the maximum distance to the coastline. Thus, independently of the island, the plant is bonded to the coastline which means that this criterion is most likely one of the most influential ones. Furthermore, as no pure economic analysis was conducted, more flexibility is achieved while allowing larger eligible areas which in turn enables other criteria to affect site selection.

Ports represent a potential risk of oil spill water pollution. Given that one of the disadvantages of RO technologies, when compared to thermal ones, is handling such contaminations, ports are excluded. Additionally, any PV park located within the shoreline and maximum distance to the shoreline was excluded as it represents an unavailable area. No buffer is needed for PV parks while ports are assumed to be part of industrial sites thus accounted for in that exclusion.

b) Sociopolitical category

The sociopolitical category consists of constraints that include both social and political interests. The desalination plant should not compromise existing infrastructure such as airports and military areas. Nevertheless, they also represent areas that are not available. The same applies to commercial and industrial areas criterion. SWRO desalination plants don’t pose a threat to these infrastructures, so no buffer distances were considered except for very high-frequency omnidirectional range (VOR) radars and general communication equipment types of airports. Such airports require a buffer to safeguard proper functioning as electric interference may cause navigation errors. Therefore, based on Winkler's study [70], a buffer of 100 m was applied to both.

Furthermore, settlements and croplands are also exclusions. The exclusion of settlements, apart from being physically unavailable, considers social preferences as noise and visual impacts of a desalination plant may originate conflicts with the population. The average and median of the literature values (1 000, 1 200, 1 500, up to 4 000 m [14, 16, 18, 25]) are 1 925 and 1 350 m. Prior to selecting a buffer, a technology strongly related to noise effects and visual impact (wind turbines) was compared to desalination plants. For instance, the noise level of wind turbines ranging from 102 to 108 dB can be found in the literature [113, 114] while for high-pressure pumps (the noisiest component of desalination plants), it varies from 90 to 110 dB [25]. These similar ranges allow a noise-based comparison to be established. Also, some of the literature studies consider desalination in general (e.g., in [14, 16, 18]) thus the impacts of thermal technologies were probably included in the respective buffers. Hence, as buffers as low as 500 m were found for wind turbines [115] and knowing that RO technology has lower visual, sound[7], and odor[8] impacts than thermal technologies, a lower value than the ones in the literature should be selected. For example, power plants, also noisy places, display acceptable dB levels at 300 m (43 dB) [116]. On top of that, noisy components are often locked in rooms to reduce the transmission of sounds. Such reasons lead to 300 m being applied to clustered settlements and 200 m to isolated ones (to avoid overlapping off buffer distances).

Additionally, recreational and cultural sites are excluded due to their high value attributed by the population and a possible source of income to countries dependent on tourism (Caribbean Island states, Cabo Verde, for the case of beach). As the same reasoning behind settlements applies to recreational sites, the same buffer is also considered. Turning to croplands, its conflicts with renewable energy were added to the desalination "learning curve". Thus, any cropland in the vicinity of the studied area should be excluded in order not to add up to this conflict and to avoid brine spill soil contamination. Even though desalination plants are frequently monitored, and a pipeline is unlikely to break, a buffer of 100 m is applied to croplands to account for any sudden accident with brine concentrate.

c) Nature conservation areas category

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[7] It is compact technology.

[8] No steam is boiled.

Nature conservation areas category including reserves, parks, forests, and sites with important flora and fauna are considered exclusions. By doing so, biodiversity is preserved, ecosystems are protected, and endangered species are accounted for, sustainably. Desalination plants have the potential to negatively impact these areas given that it is related to both marines, through intake pipelines and brine disposal, and terrestrial areas due to the significant required footprint.

Bartolomei et al. [13] considered a buffer of 3 000 m to minimize the environmental impacts while Gholamalifard et al. [18] simply stated a buffer of 7 000 m to inland protected areas. Additionally, Sepehr et al [16] considered buffers higher than 1 000 m (not stating a maximum value and considering several categories). However, these studies consider desalination plants, in general, different from the current one that focuses on reverse osmosis technology. It means that the above-mentioned buffer distances may be based on the environmental impacts of thermal technologies. As such, a different approach is required. For terrestrial-protected areas and bird-protected areas, a buffer of 100 m is applied given the low impact of RO technologies. Marine-protected areas however should account for brine disposal thus a buffer is required. Maintaining the same approach as in slope (upper value of the medium category), the 3 000 m buffer suggested by Sepehr et al. [16] is considered which coincides with the median of all stated values. To the world heritage protected areas, a buffer of 1000 m was applied based on [70].

A summary of all criteria and respective buffer distances considered in the current work is shown in Table 12.

6.3. Seawater Reverse Osmosis desalination plant’s capacity

Regarding the desalination plant’s capacity, the current work follows Heinrichs et al. [106]. The mentioned paper considered stoichiometry (9 m^3 of water per ton of hydrogen), assessment of water availability and demand, and existing plants to estimate an average capacity of 367 000 m^3/day for future desalination plants. Due to an in-depth study of the desalination plant’s capacity, focus on reverse osmosis technology, and having desalination as a possible solution for water competition, the study described is viewed by the author as a pertinent one. Thus, the chosen plant’s capacity is 367 000 m^3/day.

Table 12 – Exclusion Criteria and buffer distances considered

Category	Exclusions	Min	Median	Average	Max	Buffer [m]
Physical	Water bodies	400				400
	Land slope	8°	12°	12.25°	17°	12°
	Max. Elevation	1 500				1 000
	Min. Elevation					2
	Wetlands	1 000	2 500	2 500	4 000	100
	Mining Sites					100*
	Dunes					1 000*
	Glaciers					1 000
	Borders					0*
	Flood Areas					0*
	Max. distance to Shoreline	300	1 500	2 543	10 000	2 500
	Min distance to Shoreline	100				100
Sociopolitical	Settlements (Clusters)	1 000	1 350	1 925	4 000	300
	Settlements (Isolated)					200
	Heritage/Recreational Sites					300
	Airports (VOR-Radars)					100*
	Airports (General Communication Equipment)					100*
	Airports (all remaining ones)					0*
	Agricultural areas					100
	Military areas					0*
	Commercial and Industrial zones					0*
	Roads (Primary)					30*
	Roads (others)					0*
	PV parks					0
Nature conservation areas	Marine protected areas	1 000	3 000	3 667	7 000	3 000
	Terrestrial protected areas					100*
	Bird protected areas					100*
	World Heritage Sites					1 000*

Buffers with “*” were based on OFPV [70]

6.4. Seawater Reverse Osmosis desalination plant’s footprint

Most studies only provide information about the capacity, desalination technology, recovery rate, source of energy, and/or cost. Thus, to determine the plant’s footprint, six existing desalination plants (RO technology only) were selected. All plants were developed by IDE Technologies which specializes in the development, engineering, construction, and operation of desalination and industrial water treatment plants. Table 13 highlights the plants considered by providing the location, commission date, capacity, and footprint.

Table 13 – Existing SWRO Plants and respective specifications

Location	**Commission Date**	**Capacity [m^3/day]**	**Footprint [m^2]**
Ashkelon, Israel	2005	396 000	70 000
Hadera, Israel	2009	525 000	150 000
Cape Preston, WA, Australia	2013	140 000	54 000
Sorek I, Israel	2013	624 000	100 000
Encina Power Station, Carlsbad, California	2015	204 412	22 258
Santa Barbara, USA	2017	10 560	5 869
Average		**316 662**	**67 021.17**

Source: IDE Technologies [117]

Based on these six plants, an average capacity and footprint of 316 662 m^3/day and 67 021 m^2 was calculated. These values are in line with Voutchkov [15] which suggests a required area in the range of 58 700 – 83 000 m^2 for a plant with a capacity of 300 000 m^3/day. Additionally, there is not a huge difference between these six plants' average capacity and the one considered, which is advantageous from a consistency viewpoint. Therefore, Table 13 indirectly suggests that 0.212 m^2 is needed for each meter cube of desalinated water per day which means that the previously chosen capacity (367 000 m^3/day) would require 77 804 m^2.

6.5. Capacity Density for Seawater Reverse Osmosis desalination

The capacity density is obtained by the ratio between the plant's capacity (m^3/day) and the plant's footprint (m^2). Therefore, with the capacity and footprint previously determined, a capacity density of 4.717 (m^3/day)/ m^2 was calculated. It is a crucial value that, along with the total eligible area, allows the calculation of the maximum installable capacity in a certain region which ultimately leads to the maximum water generated over a certain time range.

7. Scenarios

In order to achieve different system configurations and to explore different alternatives, three scenarios are considered. It refers to the Baseline Scenario, Mixed-Use Scenario, and 100% RE Scenario.

Baseline Scenario – in this scenario, trends seen in small island energy systems are taken into consideration. As seen in the literature review section, several small islands have intermediate storage with the objective of lowering costs. Therefore, the Baseline Scenario considers a centralized availability of synfuels in Sao Vicente (here as the intermediate storage), from which it is transported to the other islands. The only transmission technology considered is a vessel carrying synfuels. Moreover, only synfuels are allowed to be stored. No data was found regarding storage capacity per island apart from a 35 000 m^3 storage in Sao Vicente [50]. It is likely that the other islands do not have such big storage, however, due to the lack of data, this value was set as the maximum capacity for the remaining islands. Energy sources include RE as well as synfuel purchases. This scenario is applied to the 2022 demand.

Mixed-Use Scenario – It represents a scenario where volumes of synfuel are not enough to justify a delivery by vessel. Therefore, the only exclusion is the distribution of synfuels by using a specific vessel. Conversely, all the other transmission technologies are considered along with the option of using existing routes for energy carrier delivery. The aim of this scenario is to assess the changes in investment caused by considering available routes for fuel delivery. Here, only the 2022 demand is considered given that assumption regarding the available routes and/or available space in the ships would be highly inaccurate.

100 % RE Scenario – As the name suggests, only RE sources are considered. Therefore, the FINE framework is forced to find the optimal configuration that fulfills demand in a sustainable way. It aims at analyzing the investment need to fulfill the 2050 electricity demand.

8. Sensitivity Analysis

The objective of this sensitivity analysis is to assess the consistency of the results. To do that, an increase/decrease of 25% in the cost of fuel (to simulate market fluctuations/disruption) was applied to the Baseline Scenario and a hydrogen demand (as hydrogen is expected to play an important role in the sustainable world) was applied to the 100% RE Scenario. By varying the input parameters, it is possible that the configuration would change, thus being a piece of insightful additional information.

9. Concluding remarks

In the present chapter, a detailed explanation for both energy provision and SWRO desalination site selection were presented. Also, the reasons behind the choices made as well as the assumption can also be found in this chapter. On top of that, the scenarios considered and sensitivity analysis included were also described.

Chapter 3: Results and Discussion

1. Introduction

In this chapter, first, results are presented regarding both LEA and energy provision optimization in the case study country, Cape Verde. The following sub-section focuses on analyzing the different results and highlighting important aspects of them.

2. Results

2.1. Land Eligibility assessment for SWRO desalination

Using the methodology outlined in the LEA section, eligibility at the regional level was obtained for the 22 regions of Cape Verde, as Figure 8 reports.

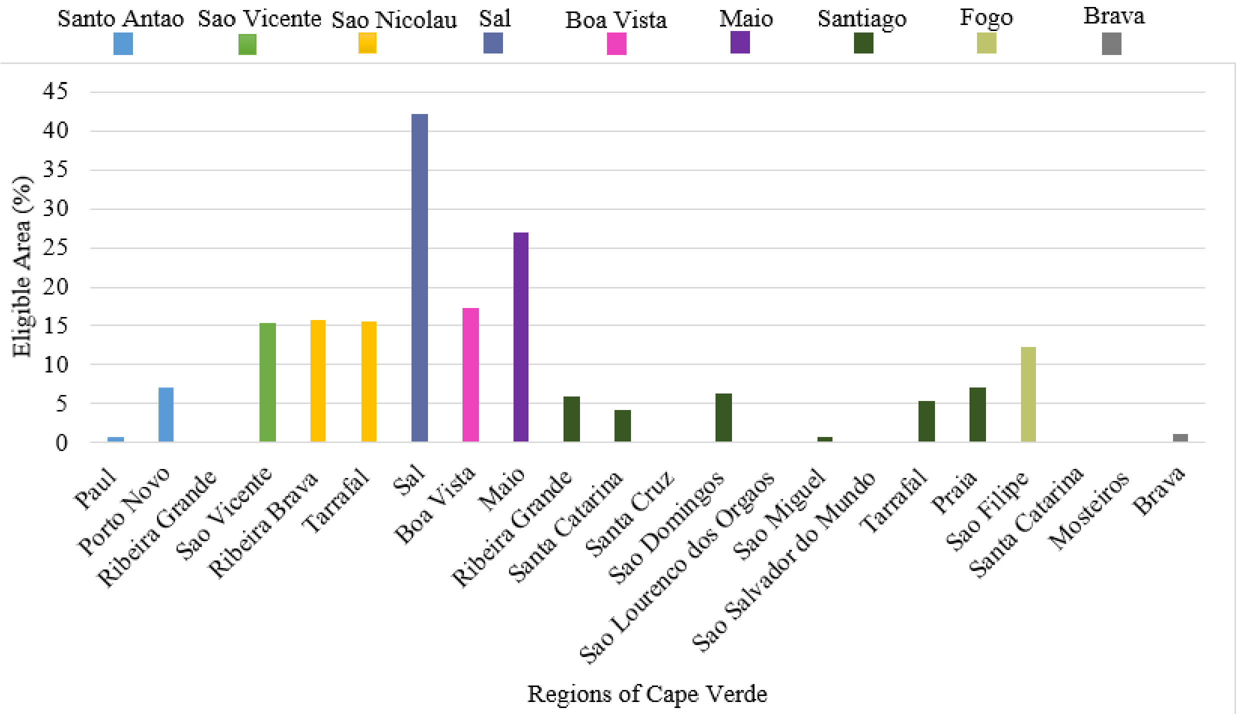

Figure 8 – LEA results

Figure 8 shows that land eligibility values range from 0, in Ribeira Grande for example, to a maximum of 42.19% in Sal. In general, 55% of regions display values lower than 10%. Better comparisons, however, are enabled by the following Table 14 which displays the results only at an island level.

Results show that land eligibility for SWRO plants in Cape Verde is below 30% in most of the islands, with only Sao Nicolau (31%) and Sal (42%) contradicting such a trend. The island of Brava accounts for the lowest eligibility (1%) among the islands while Sal (42%) has the highest. Regions with 0 eligibility are not listed in the table.

Table 14 – Land eligible & water generation and hydrogen maximum potential per island

Islands	Eligibility (%)	Area Eligible (m^2)	Max Capacity (m^3/day)	H_2/day (ton)
Santo Antao	7.9154	62 385 391.8	294 271 893.1	29 427 189.31
Sao Vicente	15.3912	34 597 808.93	163 197 864.7	16 319 786.47
Sao Nicolau	31.3792	108 534 209.4	511 955 865.8	51 195 586.58
Sal	42.1902	93 982 945.05	443 317 551.8	44 331 755.18
Boa Vista	17.3312	110 682 216	522 088 012.7	52 208 801.27
Maio	26.8678	72 938 046.01	344 048 763	34 404 876.3
Santiago	29.8702	299 096 503.5	1 410 838 207	141 083 820.7
Fogo	12.3155	57 598 178.13	271 690 606.3	27 169 060.63
Brava	1.0651	687 386.2982	3 242 401.169	324 240.1169
CAPE VERDE		840 502 685.1	3 964 651 166	396 465 116.6

Among all regions, the slope is the most frequent exclusion criterion. In fact, it is the criterion with the most impact in 17 of the 22 regions. Its impact ranges from 8% in Boa Vista to 94% in Paul, Santo Antao, with an average of exclusion 47% all over the country. Another important criterion is the isolated settlement that significantly impacted land eligibility. Ranging from 8.5% in Boa Vista to 75% in Sao Salvador do Mundo, Santiago, this criterion is among the top three most influential ones, appearing in 16 of the 22 regions. The third most frequent one refers to wetlands with 14 appearances in the top 3 most impactful criteria. Regions such as Sao Lourenco dos Orgaos (95%) and Santa Cruz (76%) were heavily impacted by this criterion.

Out of 4 025 km^2, only 841 km^2 are available for SWRO plants in Cape Verde (21%) which means that Cape Verde has enough land available for a theoretical installable capacity of 3.9 billion m^3/day. Moreover, strictly based on the LEA results and 10 liters of water requirement per kg of hydrogen, a theoretical 0.4 billion tons of hydrogen per day could be produced in Cape Verde provided that enough energy would have been made available.

At a global level, the desalination potential per country given by the developed criteria is shown in Figure 9. Potential per country reaches values as high as 6 000 km^3/day with countries like USA, Russia, Australia, Argentina and South Africa having huge potentials. However, countries with no coastal areas like Niger have, naturally, no potential. See Appendix 8 for more maps. Further, West and Central Africa countries display low potential if compared to South Africa, USA, etc., which should be taking into account for future green hydrogen production.

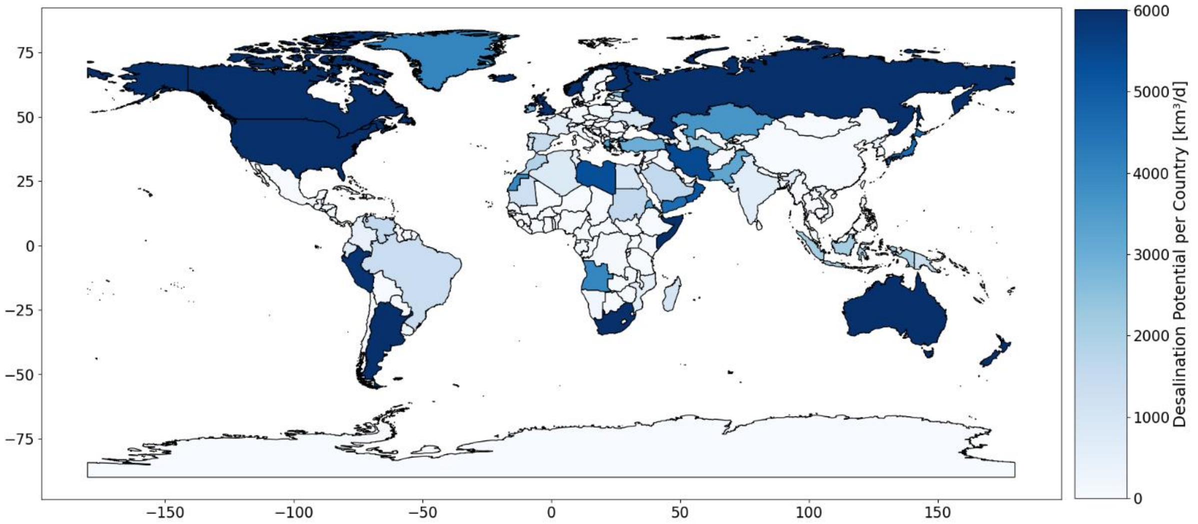

Figure 9 – Desalination potential per country

2.2. Energy Provision

After clustering the time series data into 15 typical periods and 24-time steps each (360 h), the optimization results for the different scenarios are shown as follows.

a) Baseline Scenario

In this scenario, the energy mix is composed of all generation technologies available. Regarding RE, there is a clear dominance of wind over solar not only in the number of islands involved (8 for wind, 6 for PV out of a total of 9 islands) but also in the total capacity installed by technology. A total of 134.6 MW of wind turbines were installed while only 7.1 MW are deployed for PV. Naturally, a higher investment is verified in the wind turbines as well (around 170.8 million euros) with PV accounting for approximately 10.2 million euros. Another generation involves the use of power plants. In fact, the total capacity installed amounts to 80.1 MW, which causes an investment of approximately 65.3 million euros (M€). See Figure 10 for the distribution of wind turbine and synfuel power plant capacities in Cape Verde. In terms of total annual cost (TAC), wind turbines and synfuel purchases account for the highest ones, 21.7 and 15.4 M€, respectively. The third highest one comes from the power plants (13.96 M€) while PV displays a TAC of around 1.21 M€.

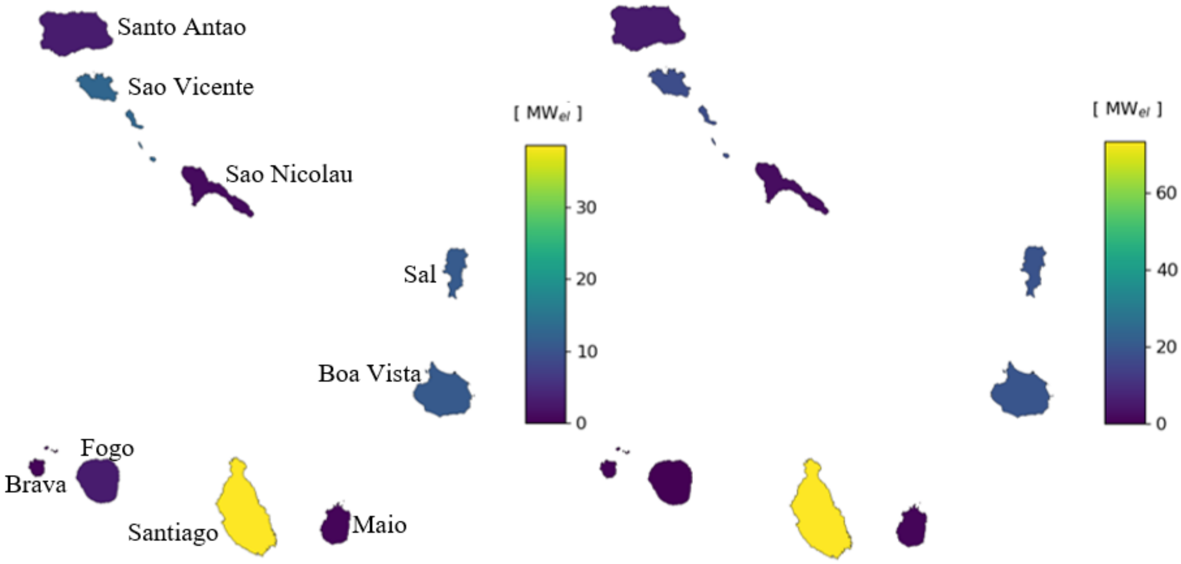

Figure 10 – Synfuel Power plants (left side) and wind turbine (right side) installed capacities

The optimal solution found does not include the storage of synfuel. As for fuel distribution, capacities vary from 1.2 (Brava) to 92 MW (Santiago), totaling 163.2 MW. All distribution lines are direct links and start at the focal point for synfuels availability, Sao Vicente, and amount to a TAC of 4.22 M€. The total investment required in the Baseline Scenario is around 246 M€.

b) Mixed-Use Scenario

Different from the Baseline scenario where RE is deployed on several islands, in the Mixed-Use scenario a tendency towards centralizing the energy system on Sao Vicente is verified. With PV no longer part of the optimal solution, wind energy still dominates the energy mix with a total of 115.5 MW (108.04 MW in Sao Vicente and the remaining part in Brava). Compared to the Baseline scenario, wind energy capacity decreased by 15%. A similar decrease is also seen in the investment, which was lowered to 146.6 M€. The TAC also reduced to 18.59 M€. Power plants are no longer utilized on all islands, which is the case of Boa Vista, Maio, and Brava that do not have any capacity installed. Hence, a decrease of 2.5 MW (3.12%), 0.6 M€ (4.29 %), and 2.9 M€ (4.4%) are noted in the total installed capacity, TAC, and investment, respectively, if compared to the Baseline scenario. As for the synfuel purchase, the TAC was reduced by roughly 18.8% (12.5 M€).

Different from the previous scenario, the current one includes storage. The optimal solution suggests battery capacities ranging from 0.01 to 0.93 MW on five islands (Boa Vista, Brava, Fogo, Maio, Santiago) which amount to 1.3 MWh at a national level. Thus, batteries would require an investment of 513 708 € with a TAC of 72 859 €. Synfuel storage is also included but with much higher capacities. It is present on four islands (Fogo, Sal, Santiago, and Sao Nicolau) with capacities ranging from 311 to 71 533 MWh. It totals 80 618 MWh, which would require an investment of 6.98 M€ and TAC of 759 689 €. The distribution of batteries and wind energy capacities is reported in Figure 11.

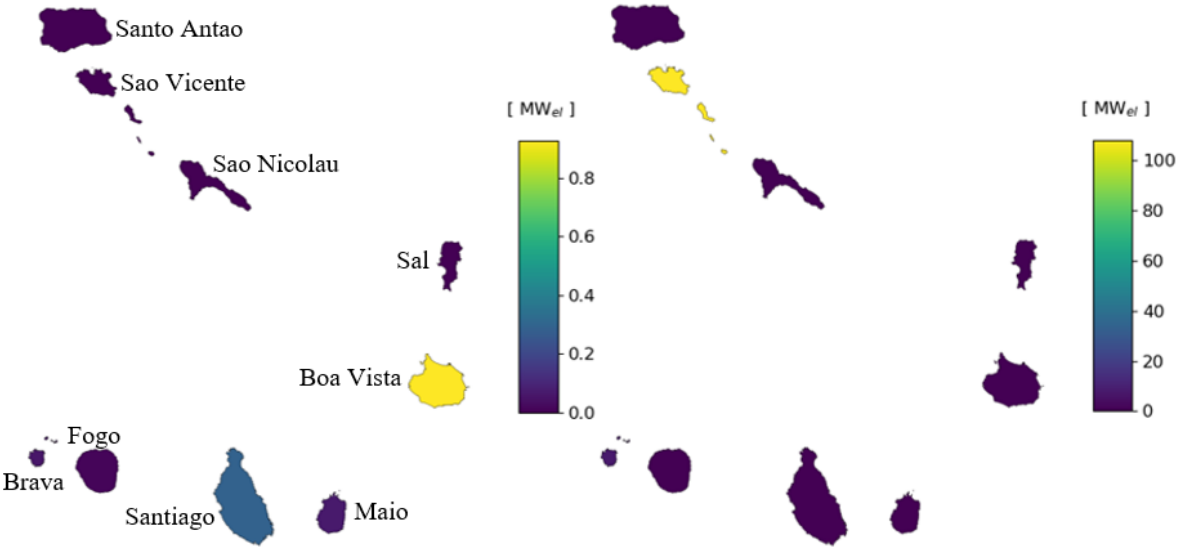

Figure 11 – Batteries (left side) and onshore wind (right side) installed capacities per island

Regarding fuel distribution, the maximum capacity of cargo is part of the solution which totals 2.99 MW. The same occurs to fuel trucks which total 204 MW while containers were not part of the solution. However, the major distribution alternative is DC power cables with capacities ranging from 2.5 MW to 3 000 MW. It accounts for 9 091 MW in total and a total investment of 810.4 M€. Further, the hydrogen alternatives are not cost-effective even with the highest efficiencies in the electrolyzer and fuel cell, thus not being part of the optimal solution. All in all, this scenario would require an investment slightly higher than 1 billion euros mostly driven by the subsea cables. See Figure 12 for DC subsea cables interconnections.

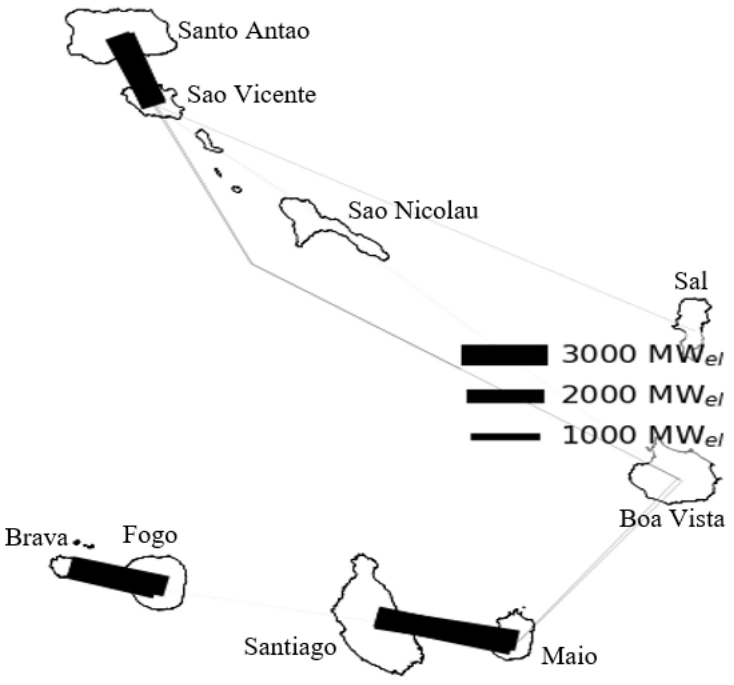

Figure 12– DC-Interconnections

c) 100 % RE Scenario

Applying the 100% RE scenario to the 2050-electricity demand yields a new configuration for the energy system. Even though Sao Vicente continues to have large RE capacities, the inclusion of other islands is verified. PV is now utilized in Boa Vista and Maio apart from Sao Vicente. Its capacity ranges from 35.6 to 143.7 MW, totaling 275 MW. For such PV deployment, a TAC of 46.8 M€ and an investment cost of 393.5 M€ are attached. Similarly, wind capacity increased to 2 328 MW split in 3 islands (667.8 MW in Sao Vicente, 541.8 MW in Sal, and 1 118 MW in Boa Vista). Hence, a large investment is needed, 2 954 M€, along with a TAC of 374.8 M€. Furthermore, batteries are now deployed to all islands with capacities ranging from 0.23 to 352.6 MWh (1 892 MWh in total). An investment of 720.9 M€ would be needed along with a TAC of 102.2 M€. Similarly, to the Mixed-Use scenario, subsea power cables play an important role with a total of 9 344 MW installed in the country. Subsea cables account for an investment of 1 477 M€. This scenario requires an investment of 5 546 M€. The distribution of RE generation capacity is shown in the following Figure 13.

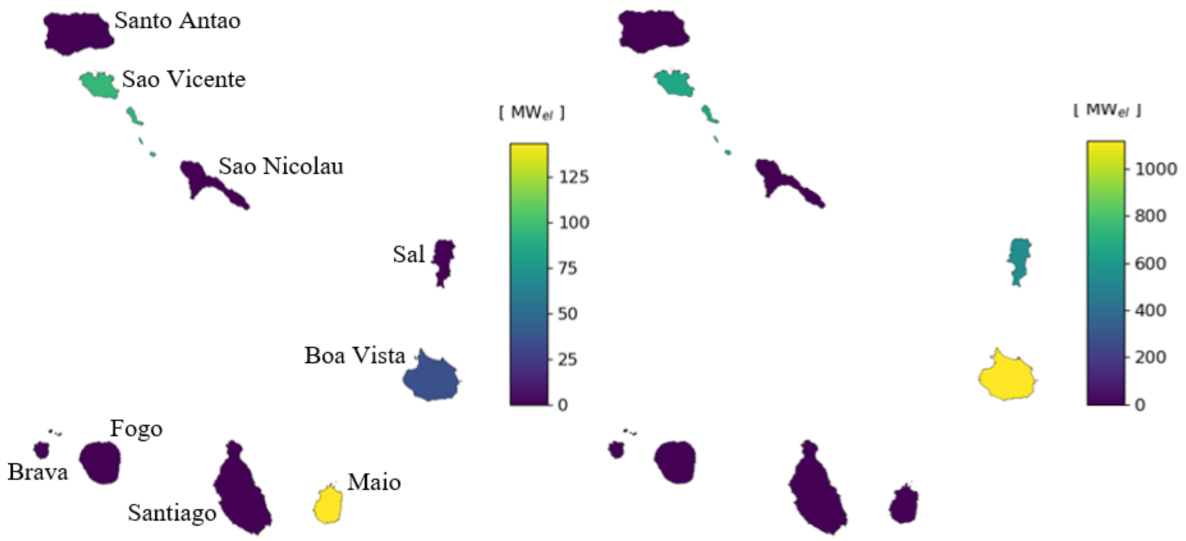

Figure 13 – PV (right side) and onshore wind (left side) installed capacities

3. Discussion

3.1. Land Eligibility assessment for SWRO desalination

Even though the current work's focus is at the island level, much more insightful results for the LEA assessment are seen in Figure 8, at the regional level. As seen previously, land eligibility is quite low due to significant exclusion caused by slope criteria, isolated settlements, and wetlands. Focusing on slope, a good example is Santo Antao. Known as the 'mountainous island', it has, on average, an 85% exclusion caused by this criterion. High-elevation land can be pinpointed as the reason, which can be seen in Ribeira Grande (with no land eligible) using OpenStreetMap [118]. In fact, and again based on OpenStreetMap, a fast increase in elevation can be verified all over the island. Using trigonometry on the maximum distance to the coastline (2 500 m) and slope (12°) yields that the rapid increase in elevation is threatening as elevations of 520 m end up being a break-even point between eligible and ineligible land.

Moreover, physical characteristics also affect how settlements are built, especially in countries with high slopes. Given the difficult terrain, houses tend to be built in a scattered way. High shares of the population living in rural areas also add up to that. As such, houses are often surrounded by agricultural fields thus falling into the category of isolated settlements. These might be possible explanations for the case of isolated settlements given the high slope and significant rural population (26% in 2021 [119]) of the Cape Verdean islands. Furthermore, several wetlands are found in Cape Verde which are important for animals and plants. The salt flats in Sal and Maio are examples of that. Besides that, flat land in Boa Vista allows the existence of masses of water on the island such as the lagoon of Rabil. It also extends to Santiago with Pedra Badejo and the reservoir in Poilao being a few examples (much more can be found in [120]). Hence, these examples show that the wetland criterion should indeed be frequently found among the results.

The maximum distance to the coastline criterion is not part of the most frequent ones, however, its significance should not be neglected. Santiago, where Sao Lourenco dos Orgaos and Sao Salvador do Mundo are completely excluded, can be used as an example in this regard. Being located towards the center of the island and the only regions without contact with the sea, these two regions would be ruled out by this criterion at an island level. The reason why it is not part of the most impactful ones in these regions is that the calculation was performed by region, thus regions with no coastal areas are not affected by this criterion.

It should be noted that, for regions with 0% eligibility, it does not mean a desalination plant can’t be built. It means that, according to the constraints set, desalination plants are expensive to be built in such locations as higher altitudes, and/or larger distances from the coastline would be unavoidable.

Similar reasons could be stated regarding low eligibility on the other Cape Verdean islands, except for Sal, Boa Vista, and Maio. These islands' topography is quite different. For example, Sal's highest point is below 400 m thus, from an elevation standpoint, it would be completely eligible. The same can be said about Boa Vista and Maio with slight deviations in their highest points. These islands have, therefore, many more coastal areas available to be processed by other criteria such as settlements. Such is the case of Sal and Maio which have isolated settlements as the most impactful criterion, however, with far lower impact if compared to the slope on other regions. Thus, higher eligible lands do make sense in these islands.

In the LEA results section, it was stated a maximum installable capacity of 3.9 billion m^3/day and 0.4 billion tons of hydrogen per day. It is important to emphasize that these are purely theoretical values as: (i) it is unlikely that the islands would be completely filled with desalination plants; (ii) Desalination plants at some point would have to compete with OFPV and onshore wind turbines for the available land; (iii) the exclusion criteria is not static which means that current trends concerning increase in population, for example, would probably lead to more exclusion areas; (iv) water competition between hydrogen and other uses, however to a lesser degree.

To highlight the lower impact of populational water demand, Sao Vicente and Santiago are perfect examples, due to having the highest populations and desalination contributing to 99% of water availability. In 2022, the consumption of water was 2.45 km^3 and 5.27 km^3, for Sao

Vicente and Santiago, respectively [56]. Based on the results obtained, such water consumption represents 1.5% and 0.4% of what could be produced in only one day if the total eligible area were to be utilized, which is negligible.

Even though the current study presented an innovative approach to desalination site selection, thus different from existing ones, a comparison can still be made. Like Majoobi and Behzadi’s study [12], which held distance to a water source (river) and slope as the most influential criteria, the current study also supports the relevance of the slope criteria which significantly impacted islands such as Santo Antao and Santiago. Other similarities are found in studies that considered categories for site suitability (very high, high, medium, low, very low) despite the differences. Assuming that the classes very high, high, and medium are equivalent to the current study, the results found in the current study (1 to 42%) are in the same range as [18] (40%), [14] (40%), [21] (42%), and [22] (<10%).

All in all, the LEA assessment applied on Cape Verde yielded that (i) slope, wetlands, and isolated settlements are the key criteria. Therefore, criteria-oriented detailed assessments would lead to more precise results, especially in the case of slope. Any variation in this criterion is likely to heavily impact affect land eligibility. Nevertheless, a trade-off between available land and capital investment is unavoidable as more eligible areas would lead to the inclusion of suboptimal sites that, in turn, leads to higher costs; (ii) any green hydrogen production in Cape Verde is most likely to be limited by RE generation. As shown before, huge amounts of water can be generated, however, it is a process that heavily relies on energy thus further stressing energy systems; (iii) the impact of water demand is negligible, hence, freshwater potential from desalination plants by far outcomes the island's water demand which presents an opportunity for other uses.

The lack of regulation is a barrier to correct exclusion criteria. Even though the most realistic ones, scientifically based, were the priority in the current work, whether the applied criteria deliver the optimal solution for all involved stakeholders is uncertain. The author's understanding is embodied in it, meaning that others might opt for different criteria and/or buffer distances. As such, the current assessment should not be taken as the truth, but rather as a solid base to be built upon.

3.2. Energy Provision

The Baseline Scenario was considered with the objective of representing existing energy systems, which was partially achieved. Such is the case of the energy mix having RE and non-

RE sources. As the actual energy system in Cape Verde [56], the energy mix obtained includes wind, solar, and a non-RE source (oil in Cape Verde, synfuels in the current Baseline Scenario). However, two major differences can be pinpointed.

First, there is an over-utilization of RE, particularly wind energy, if compared to Cape Verde's actual status. It is partially caused by the existing RE capacity (see case study section), which was not considered in the model. By considering the total consumption but not the total generation capacity, the FINE framework is obliged to include RE in order to ensure energy security. Given the high base CAPEX of wind turbines as well as higher generation from wind energy sources in 7 of the 9 islands (with Santo Antao and Fogo being the exceptions), it does make sense to have higher utilization of wind turbines as (i) more energy can be generated from wind turbines than from PV and (ii) scaling up wind parks would compensate the high base CAPEX and more advantageous as the cost per capacity is lower for wind turbines if compared to PV.

Nevertheless, given the high solar potential on islands like Santiago and PV's significant cost advantage in base CAPEX, one would expect PV to have greater utilization. However, even in these islands, results show that it is more advantageous to include wind turbines and scale them up instead of PV, despite the base CAPEX of wind turbines being higher than PV. An interesting case is Brava. Considering what was previously discussed, FINE still chooses wind parks with capacities as small as 0.62 MW, instead of PV technology. A closer look at the generation time series reveals that, in Brava, wind energy outperforms PV by a factor slightly higher than 2. This means that, on the one hand, much more energy can be generated by wind turbines. On the other hand, with PV systems only generate energy in daylight hours thus an additional cost in batteries would be required. These reasons justify FINE's choice.

Moreover, the larger utilization of RE leads to the underutilization of power plants. As displayed in the results sections, none of the synfuel power plants are being used to their fullest capacities (see appendix 10). Given the intermittency of RE, synfuels are being used to generate energy in low RE generation times. Therefore, the combination of on-site RE and synfuel power plants is more cost-effective than a system purely based in synfuel purchase and distribution.

Secondly, synfuel storage is absent from the optimal configuration which is not the case in real energy systems. Storage is crucial to ensure energy security. Due to various reasons, supplies of fuel are often made in an intermittent way, especially in small island states (see [3] for more details). However, this dimension was not incorporated which means that, from the model perspective, it is possible to deliver synfuel whenever it is needed. Thus, with a reliable supply, the model avoids extra costs in storage. On the other hand, storage can allow economies of scale. Bigger vessels can deliver large amounts of energy in lower frequencies different from smaller ones which would require higher trip frequencies to deliver the same amount of energy. Hence, by only considering one vessel option, economies of scale were also not incorporated in the present approach.

Regarding the Mixed-Use Scenario, a significant change in the system's configuration is verified. With severe constraints set to synfuel distribution, the most cost-effective solution tends to centralize energy generation in the RE-rich island, Sao Vicente. Due to these constraints (limited capacity due to space restrictions in existing routes), storage now plays an important role. Different from the Baseline Scenario, where energy could be delivered without any bottlenecks, the current limitations motivate the inclusion of synfuel storage. Hence, large synfuel storage is now included for instance in Santiago which is the island with the highest demand and the most ship connections. Similarly, batteries are now considered. With higher shares of intermittent energy sources in the energy mix, energy storage is crucial to ensure a steady energy supply, enhance RE integration as well as to smooth imbalances between supply and demand, which may be particularly important during peak demands.

Additionally, synfuel power plants cease to be utilized on all islands. Such is the case with Boa Vista, Maio and Brava. It is partially caused by the limited amounts of synfuel that can be delivered through existing routes which would not be enough to power the islands. On top of that, the subsea power cable transmission option also plays an important role. In fact, it allows islands like Boa Vista and Maio to depend on RE-rich islands and battery storage. Taking Santo Antao as an example, its energy demand is fully supplied by Sao Vicente given the absence of storage. With a limited supply of synfuels, the subsea cable must be large enough to deal with peak demands, which may be a reason behind its high capacity. Nevertheless, given the high investment in subsea power cables, results suggest that it is more cost effective to have a big power cable connection instead of battery storage and/or onsite RE generation in Santo Antao. This is one of the impacts of base CAPEX.

Even though the incorporation of storage and subsea power cables allowed a decrease in RE capacity deployed (compared to the previous scenario), the overall cost increased exponentially. In fact, the current scenario's investment increased by a factor of 4 (1 027 M€) which was mostly caused by the DC subsea cables (80%). Despite the inclusion of existing routes in energy provision, most likely due to the low costs, the increase in overall cost suggest that the Baseline

Scenario is better. The side effect of attempting to lower transmission costs by using existing infrastructure would cause severe restrictions on fuel delivery which would require significant investment in alternatives. Moreover, relying on existing shipping routes would increase uncertainties regarding energy provision. One of the disadvantages of energy delivery by vessel is the dependence on weather conditions, thus if fuel were to be delivered through existing shipping routes, a second uncertainty – maximum amount transmissible – would be added. As such, this scenario is not beneficial for Cape Verde and possibly any other island states that displays similar energy consumption level as the ones in Cape Verde.

The last scenario, 100% RE, forces the energy mix to be fully renewable. Applied to the 2050 demand, a large scale-up in RE is verified as expected. Wind energy deployment reaches 2 328 MW, a value 20 times higher than the one in the Mixed-Used Scenario. On top of that, PV is also utilized on several islands with a total capacity of 275 MW. Such massive deployment of RE is caused by the huge demand in 2050 which is 4 times greater than 2022's demand. With such a huge gap between energy demands, power generation needs to grow exponentially. Consequentially, Sao Vicente RE is no longer sufficient. Other RE-rich islands like Sal and Boa Vista, for wind energy, as well as Maio, for solar energy, are no longer sinks but sources. Moreover, since only intermittent sources are being considered, it does make sense that batteries are used on all islands. As stated previously, batteries are crucial in the integration of intermittent energy sources, especially in this scenario with no synfuels. On top of that, it is likely that the maximum capacity allowed for subsea power cables is no longer sufficient for such high energy demand, thus supporting the battery usage in all islands.

The 100% RE Scenario's results also show that sustainability comes with a very high cost. A 100% RE-powered Cape Verde with 2050's demand would require a total of 5 546 M€. Apart from power cables, battery storage accounts for a large part of it.

To date, a number of studies have been carried out in Cape Verde motivated by such RE potential and energy transition. At a country level, Coutinho et al. [121] studied energy security by applying a multi-criteria analysis and a Delphi survey. The authors considered three alternatives, (i) subsea power cables, (ii) an increase in the renewable energy share, and (iii) a combination of both to assess which one could increase energy security. Results showed that energy security in Cape Verde is strongly affected by energy availability, which in turn is impacted by fossil fuel dependency and lack of auto-sufficiency. Energy-wise, the combination of subsea cables and renewable energy yielded the best results but at a higher cost. The optimal alternative to improve energy security was found to be an increase in the renewable share.

Indirect impacts were not accounted for and thus pinpointed as a limitation. Island level studies can be found in [58, 122].

Given the inclusion of subsea cables, Coutinho study [123] is better suited for comparisons than the others. In fact, the authors estimated a cost of 1 267 million dollars to interconnect the islands which is similar to the cost found in the 100% RE Scenario (1 477 M€). Also, the authors discuss that an increase in RE shares would enhance energy security but at higher costs. This is also the same in the current work. The Baseline scenario is the one with the most dependence on imported synfuel, however, the lowest costs. As the RE shares increase (Mixed-Use and 100% RE Scenarios) the overall cost grows exponentially. Coutinho [123] also concluded that investing in RE would be better than interconnecting the islands and based on overall cost, the current study suggests the same.

Nevertheless, the paper in discussion did not take into consideration base CAPEX. Given the barriers that it imposes, a centralized system is preferred as suggested by Mixed-Use Scenario. Also, with a centralized system, economies of scale would be possible and thus beneficial to the consumers.

4. Sensitivity analysis

The outcomes of sensitivity analysis on fuel cost are summarized in the following Table 15. It reflects the percentage changes in TAC, investment and capacity caused by an increase/decrease of 25% in the synfuel cost (34.3 €/MWh [76]), applied to the Baseline scenario.

Table 15 - Sensitivity Analysis results on fuel cost

		25% decrease in fuel costs	**Baseline Scenario**	**25% increase in fuel costs**
Wind	TAC (€)	-23.035	21 665 525	10.296
	Capacity (MW)	-23.035	134.589	10.296
PV	TAC (€)	0.616	1 210 291	48.228
	Capacity (MW)	0.616	7.121	48.228
SF	TAC (€)	-13.646	15 399 269	8.861
SF PP	TAC (€)	2.869	13 957 259	-1.912
	Capacity (MW)	2.869	81.137	-1.912
Local vessel	TAC (€)	-13.716	4 218 605	8.638
	Capacity (MW)	2.661	163.204	-1.701

As can be seen in Table 15, deviations of 25% on the fuel cost do not change the system configuration. Taking the Baseline as reference, it can be seen that a decrease of 25% on synfuel cost would lead to less wind turbines deployed which would enable significant savings. Even though the capacity of synfuel power plant increases, the TAC of synfuel purchase also decreases as fuel is accessible at a lower cost. Naturally, the vessel whose TAC depends on fuel consumption has a lower TAC and a slightly higher utilization. Considering the overall TAC, an increase of 9.3% is verified with an increase in synfuel cost as well as a decrease of 10% with a decrease in synfuel cost. Furthermore, synfuel would allow significant savings compared to diesel, that is used in the country. Considering the cost of diesel of 114 €/MWh (derived from [74, 124]), the TAC would increase 232% compared to the ones with synfuels in both cases (increase and decrease of 25%). Also, it should be noted that, in futures scenarios with carbon taxes, this increase would be even higher due to higher costs of diesel fuel. Similarly, sustainable synfuel would also yield higher costs. Conversely, with an increase in synfuel cost, much more RE would be installed. The higher change is verified in PV, however, due to its low capacity, wind turbines are still the most influential component. Moreover, with fuel at higher cost and more RE installed, synfuel-based components tend to be less used.

In summary, the Baseline Scenario, which has the lowest overall cost, is resilient to changes in synfuel cost. No severe changes are verified in the system configuration apart from increases and/decreases in component's capacity and/or usage. Therefore, apart from being the most cost-effective scenario, it is also resilient which makes it a solid scenario for islands. Nevertheless, islands would still be dependent on fuel imports, thus being its major downside.

As for the hydrogen sensitivity analysis, desalination plants and electrolyzer are included as expected. The future hydrogen routes can be seen in the following Figure 14.

The chosen islands for hydrogen production are Boa Vista, Sal, Santo Antao and Sao Vicente hence being the same ones with electrolyzers and desalination plants. These are the same islands with hydrogen storage which allows electrolyzers to work at optimal point. Even though Santo Antao's energy is provided by Sao Vicente, it can be seen that the optimal configuration prefers to generate hydrogen on both islands instead of building a pipeline between them. It is most likely caused by their proximity which would make the extreme investment in offshore pipeline not cost-effective for such a small distance. In fact, hydrogen pipelines seem to be more cost effective at higher distances, with the smallest length connection being Sao Vicente – Sao Nicolau (82 km). Moreover, given the highest hydrogen demand, Santiago is the island with the most pipeline connections.

All in all, results show that, based on the assumptions considered, any hydrogen distribution in Cape Verde would be done by pipelines instead of a hydrogen vessel. Routes are dependent on the islands’ demand, with higher demands leading to more connections. The impact of base CAPEX is still felt with the inclusion of the hydrogen demand. Taking Santiago as example, despite having large RE potential and the highest hydrogen demand, the optimal configuration still prefers to import hydrogen from other islands instead of local production. Furthermore, the lack of fuel cells can be justified by the low round trip efficiency of hydrogen which allows the alternatives to have the upper hand.

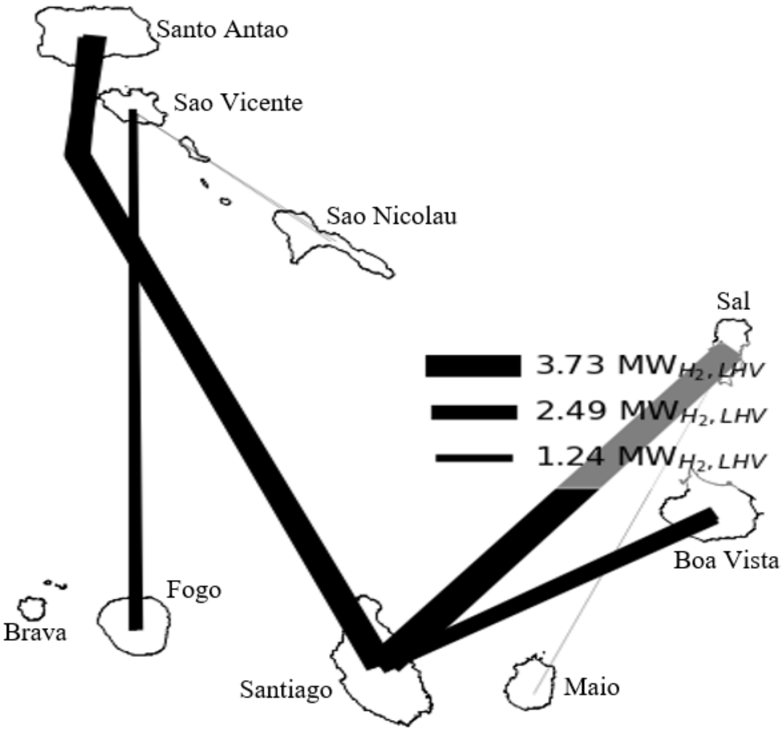

Figure 14 – 2050’s hydrogen pipelines

5. Limitation

It is a difficult task to incorporate every detail in any approach, this one being no exception. Throughout this thesis, it was mentioned that some assumptions were made which means there is room for improvement.

Regarding the desalination section, criterions related to social acceptance, local regulations as well as involving the community in the decision-making process were not taken into account. Nevertheless, these are important factors that should not be neglected. Projects that are socially accepted face less resistance which would lead to better implementation, operation, and performance. However, given their non-quantifiable nature, these criteria better fit other assessments such as multi-criteria assessments. Additionally, the lack of standards regarding buffer distances also leads to the assumption that ultimately yields inaccuracy.

The lack of data concerning base CAPEX can also be stated as a limitation. This is the case of synfuel power plants and subsea cables. Being important components of the system, any value that differs from the correct one is likely to have significant impacts. As seen in the results section, subsea cables account for a large part of the investment cost, which stresses the importance of precise values.

As of today, data regarding hydrogen infrastructures is very limited. Often, LNG infrastructures are used as a proxy by applying a factor, which was the approach applied in this thesis. However, to what degree this approach is valid is still uncertain.

Even though annual demand was converted into a demand curve, it is still dependent on assumptions that may not represent the case of Cape Verde. Therefore, a real demand curve that displays real seasonality would yield accurate results.

6. Concluding remarks

In the present chapter, the scenario and sensitivity analysis results, respective discussion as well as limitations were presented. Broadly, it can be said that energy provision is expensive in the Cape Verdean islands especially with high shares of RE. Even though the most cost-effective scenario is the Baseline, major drawbacks are synfuel import dependency and lack of economies of scale which are not beneficial to consumers. For energy demands levels as the ones displayed in Cape Verde, the utilization of existing ferry routes significantly increases the overall cost of the system as large deployment of RE and the inclusion of expensive transmission technologies, such as power cables, become necessary to ensure energy security. Additionally, a 100% RE-powered system by 2050 comes with a huge financial burden to a country where the energy sector is not the only problem. Furthermore, results show that in Cape Verde, onshore wind has the upper hand over PV. It is partially caused by its larger potential in most of the islands but also due to wind generation being possible even at night time.

Additionally, Baseline Scenario is resilient to changes in synfuel cost with no severe changes verified in the system’s configuration. Apart from being the most cost-effective scenario, it is also resilient which makes it a solid scenario for islands. However, fuel import dependency is a major downside. Besides that, the inclusion of a hydrogen demand in 2050 revels that any hydrogen distribution in Cape Verde would be done by pipelines instead of a hydrogen vessel. Also, routes would be dependent on the islands’ demand, with higher demands leading to more pipeline connections.

Conclusion and perspectives

Islands are challenging locations that often make it difficult to supply energy. Nevertheless, a cost-effective solution should be found to fulfill demand. On this context, this thesis aimed at presenting a general approach to energy provision on small islands with the ultimate goal of defining the least expensive configuration.

To achieve this objective, first, a land eligibility assessment of SWRO desalination plants was performed. Backed by literature review, which revealed the inexistence of a fixed criteria, a new set of criteria was developed in the current thesis applicable to any island. Knowing the maximum eligible lands ultimately yields the maximum amount of water that can be generated in a certain location thus being a constraint to hydrogen production.

Secondly, a general approach to energy provision on small islands was also developed. It includes generation technologies such as PV, onshore wind, and synfuel power plants. Moreover, conversion technologies involve fuel cells, electrolyzers, and desalination plants while energy can only be stored in batteries, hydrogen storage vessels, and synfuel storage vessels. Regarding energy transmission, four alternatives were considered. Provided that there is an island with excess energy and another with a deficit of energy, transmission technologies included subsea power cables, offshore pipelines, vessels, and the option of loading fuel trucks, cargo, and containers into existing shipping routes.

These developed approaches were validated by using Cape Verde, an island state highly dependent on imported fossil fuels, as a case study. To evaluate energy provision on the 9 Cape Verdean islands, three scenarios were developed: (i) Baseline scenario that aims at representing existing features of energy systems on small islands; (ii) Mixed – Use scenario that limits synfuel distribution to existing ferry routes; and (iii) 100% RE where the 2050's energy demand is provided solely by RE. Furthermore, a sensitivity analysis was performed through deviations of 25% on synfuel cost (in the Baseline scenario) as well as through the inclusion of a hydrogen demand (in the 100% RE scenario).

The land eligibility assessment results showed that land eligibility in Cape Verde (21%) is quite low mostly caused by slope, isolated settlements, and wetlands. Nevertheless, large amounts of water can be generated that by far overcomes local water consumption. It was also concluded that any possible production of hydrogen is most likely not to be limited by desalinated water potential.

Regarding energy provision, results showed an exponential increase in overall cost as large amounts of RE are deployed. The Baseline scenario is by far the least expensive one (246 M€) and it involves the deployment of all generation technologies all over the country. Onshore wind dominates energy generation in this scenario. The Mixed – Use scenario brings a different configuration to the system along with an increase in the overall investment by a factor of 4. It is mostly caused by the severe restrictions on synfuel distribution that forces the system to include expensive distribution alternatives as well as larger investments in RE. A tendency to centralize the system in Sao Vicente, a RE-rich island, is also noticed. The highest overall cost is reported in the 100% RE scenario. With an exponential increase in demand by 2050, the inclusion of even larger capacities of RE and transmission components than the Mixed–Use scenario is translated in an investment of 5 546 M€. Given the high demand, other RE-rich islands also play the role of suppliers.

Generally, it can be concluded that Cape Verde faces a very expensive future, especially if a 100% RE-powered energy system is desired. Such a system requires massive investments in RE technologies such as wind turbines and PV as well as transmission technologies such as DC cables. Even though the Baseline scenario is the least expensive, it has a higher dependence on imported synfuels and lacks economies of scale which are some of the issues pinpointed to existing island energy systems. Moreover, there is a preference towards onshore wind energy over PV. On the one hand, it is caused by the potential that suggests a higher potential for wind energy in most of the islands. On the other hand, but also related to the first one, wind energy does not have day-night variations which may lead to savings on storage.

1. Further research

As for future work:

- The application of the presented approach on a different island state. It would be insightful to consider a set of islands with energy demands much lower than Cape Verde.
- Assess the degree at which RE would limit hydrogen production in Cape Verde given that the present study highlights huge desalinated water potential in the country.
- Assess the levelized cost of electricity (LCOE) under a MILP approach.
- Assess the systems configuration changes by including intermittent synfuel delivery in Cape Verde.

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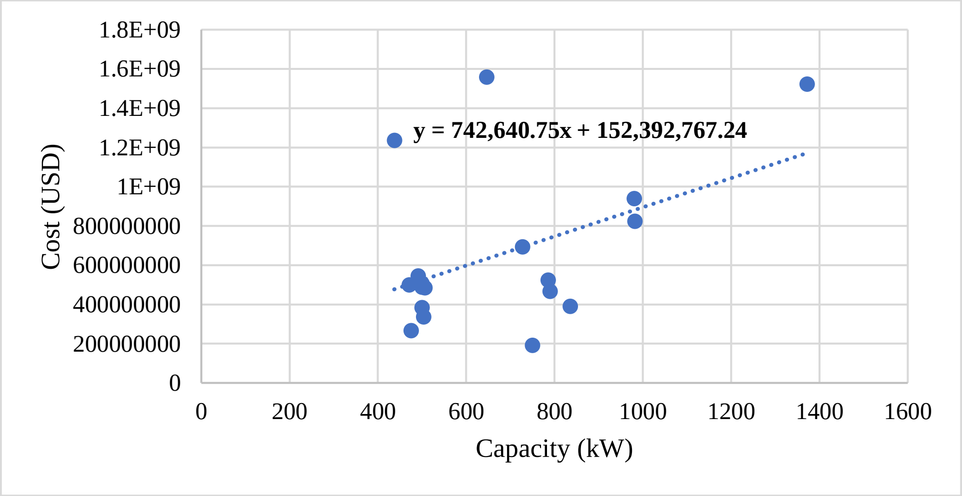
Appendixes

Appendix 1: Techno-economic parameters for the power plant

Country	Net Capacity (Mwe)	Overnight Costs per capacity (USD/kWe)	Overnight Cost (USD)	Source:
Australia	506	955	483230000	[76]
Australia	437	2826	1234962000	
Belgium	500	767	383500000	
Belgium	500	1009	504500000	
Belgium	500	974	487000000	
Canada	471	1058	498318000	
Italy	790	590	466100000	
Japan	1372	1109	1521548000	
Korea	491	1107	543537000	
Korea	982	838	822916000	
Mexico	503	669	336507000	
Mexico	785	667	523595000	
Mexico	835	466	389110000	
Romania	750	254	190500000	
USA	727	952	692104000	
USA	646	2412	1558152000	
Brazil	980	958	938840000	
China	475	560	266000000	

The column “overnight costs” was obtained by the product between the column between the columns “Net capacity” (first converted to kWe) and “Overnight costs per Capacity”. Hence, using Microsoft Excel for linear regression yields:



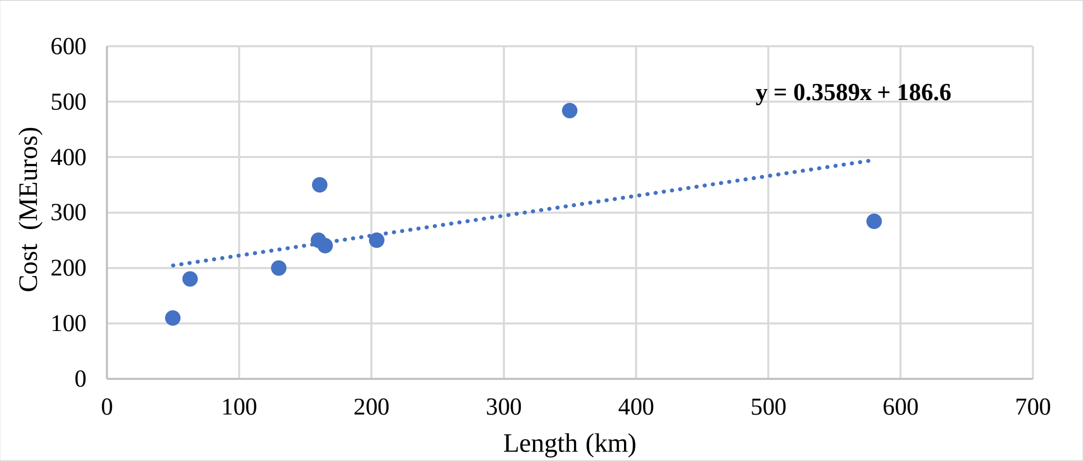
MILP approach: Base CAPEX= 152392767 USD; CAPEX=742641 USD/kW

LP approach: The average of the values in column “Overnight costs per Capacity” yields a CAPEX of 1009.5 USD/kW.

Appendix 2: DC cables base CAPEX

length (km)	Cost (Million Euros)	Source:
50	110	[91,92]
165	240	
350	484	
63	180	
580	284	
204	250	
161	350	
130	200	
160	250	

Using Microsoft Excel for linear regression yields:

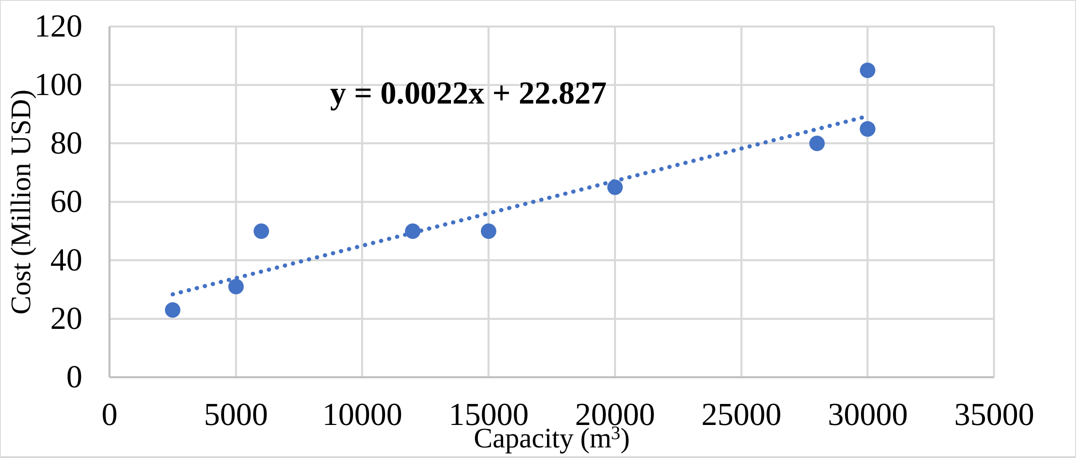


MILP approach: Base CAPEX= 186.6 million euros

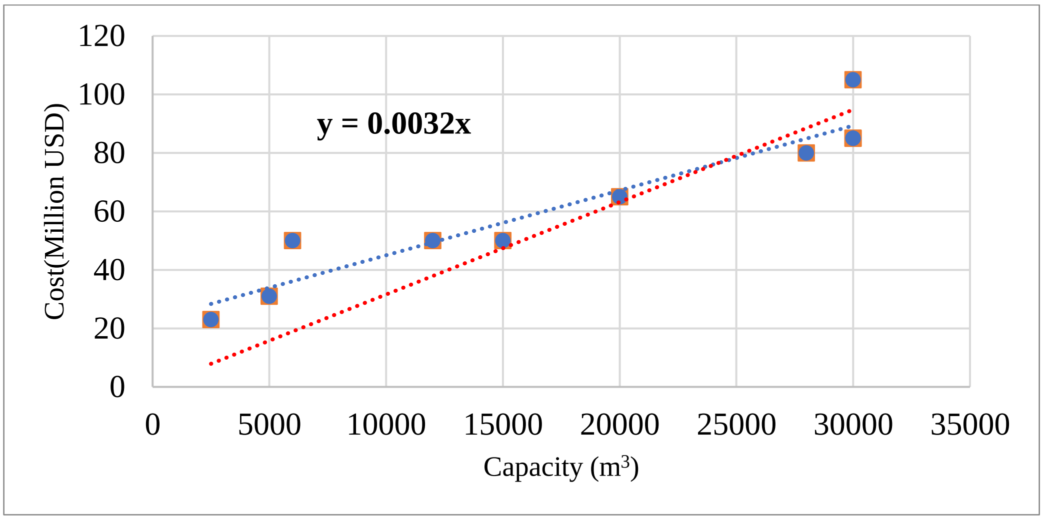
Appendix 3: Vessel techno-economic parameters

Capacity (m^3)	Cost (million USD)	Source:
5000	31	[93]
30000	85	[93]
28000	80	[94]
6000	50	[94]
12000	50	[94]
30000	105	[94]
20000	65	[93]
2500	23	[93]
15000	50	[93]
30000	85	[93]

Using Microsoft Excel, linear regression yields:



MILP approach: Base capex refers to the intersection with the y-axis (22.827 million USD) while the CAPEX per capacity refers to the slope of the curve (2200 USD/m^3).



LP approach (Red line on the graph): CAPEX is 3200 USD/m^3

Appendix 4: Cargo transportation costs

For General Cargo							
From	To	Country	Distance (km)	Cost_country currency / Per ton	Year_of_country currency	Cost (Country2023/ton)	euros2023/ton
Natovi	Buresala	Fiji	16.471	18.96	2023	18.96	7.73877551
Natovi	Savusavu	Fiji	128.444	143.12	2023	143.12	58.41632653
Natovi	Nabouwalu	Fiji	78.219	79.62	2023	79.62	32.49795918
Savusavu	Taveuni	Fiji	89.195	93.83	2023	93.83	38.29795918
Koro	Taveuni	Fiji	92.089	107.1	2023	107.1	43.71428571
Koro	Savusavu	Fiji	63.215	73.93	2023	73.93	30.1755102
Suva	Taveuni	Fiji	259.731	254.02	2023	254.02	103.6816327
Suva	Savusavu	Fiji	209.086	211.37	2023	211.37	86.27346939
Suva	Koro	Fiji	260	154.5	2023	154.5	63.06122449
Suva	Levuka	Fiji	91.577	97.63	2023	97.63	39.84897959
Suva	Kadavu	Fiji	105.763	110.9	2023	110.9	45.26530612
Fogo	Brava	Cape Verde	18.5	3317	2022	3344.1994	30.32874802
Santiago	Fogo	Cape Verde	113	3881	2022	3912.8242	35.48564096
Santiago	Maio	Cape Verde	38.9	3317	2022	3344.1994	30.32874802
Boavista	Santiago	Cape Verde	153.7	3881	2022	3912.8242	35.48564096
Sal	Boavista	Cape Verde	68.5	3317	2022	3344.1994	30.32874802
Sao Nicolau	Santiago	Cape Verde	220.4	4748	2022	4786.9336	43.41299234
Sao Nicolau	Sal	Cape Verde	159.3	3881	2022	3912.8242	35.48564096
Sao Vicente	Santiago	Cape Verde	296.3	4748	2022	4786.9336	43.41299234
Sao Vicente	Sao Nicolau	Cape Verde	81.5	3317	2022	3344.1994	30.32874802
Santo Antao	Sao Vicente	Cape Verde	14.8	3317	2022	3344.1994	30.32874802

Source: Compiled from [67, 127]

Appendix 5: Vehicles transportation costs

For Vehicles							
From	To	Country	Distance (km)	Cost / vehicle	Year	Cost (Country2023/vehicle)	euros2023/vehicle
Pico	Faial (horta)	Portugal	30.181	70	2023	70	70
S. Jorge (Velas)	Faial (horta)	Portugal	40.822	101	2023	101	101
S. Jorge (Velas)	Pico	Portugal	19.903	79	2023	79	79
Graciosa	Faial (horta)	Portugal	108.766	173	2023	173	173
Graciosa	Pico	Portugal	87.847	173	2023	173	173
Graciosa	S. Jorge (Velas)	Portugal	67.944	173	2023	173	173
Terceira	Faial (horta)	Portugal	159.291	173	2023	173	173
Terceira	Pico	Portugal	138.372	173	2023	173	173
Terceira	S. Jorge (Velas)	Portugal	118.469	173	2023	173	173
Terceira	Graciosa	Portugal	94.469	173	2023	173	173
Natovi	Buresala	Fiji	16.471	910	2015	1076.286372	439.3005601
Natovi	Savusavu	Fiji	128.444	825	2015	975.7541288	398.2669913
Natovi	Nabouwalu	Fiji	78.219	1260	2015	1490.242669	608.262314
Savusavu	Taveuni	Fiji	89.195	944	2015	1116.49927	455.7139877
Koro	Taveuni	Fiji	92.089	944	2015	1116.49927	455.7139877
Koro	Savusavu	Fiji	63.215	939	2015	1110.585608	453.3002483
Suva	Taveuni	Fiji	259.731	1100	2015	1301.005505	531.0226551
Suva	Savusavu	Fiji	209.086	1095	2015	1295.091844	528.6089158
Suva	Koro	Fiji	260	1110	2015	1312.832828	535.8501338
Suva	Kadavu	Fiji	105.763	1819	2015	2151.390012	878.1183724
Santo Antao	Sao Vicente	Cape Verde	14.8	11420	2023	11420	103.5686755

Source: Compiled from [67, 125, 126]

Appendix 6: Container transportation costs

For Containers								
From	To	Country	Distance (km)	Type	Cost_country_currency /container	Year_of_country_currency	cost in 2023	Cost (Euro2023/container)
Suva	Koro	Fiji	260	40'	2899	2015	3428.74087	1399.48607
Suva	Koro	Fiji	260	20'	1858	2015	2197.51657	896.9455393
Suva	Kadavu	Fiji	105.763	40'	3548	2015	4196.33412	1712.789437
Suva	Kadavu	Fiji	105.763	20'	2274	2015	2689.5332	1097.768652
Santiago	Maio	Cape Verde	38.9	40'	137770	2022	138899.714	1259.689965
Santiago	Maio	Cape Verde	38.9	20'	96154	2022	96942.4628	879.1770988
Santiago	Maio	Cape Verde	38.9	10'	48077	2022	48471.2314	439.5885494
Santiago	Fogo	Cape Verde	113	40'	162002	2022	163330.416	1481.253493
Santiago	Fogo	Cape Verde	113	20'	98001	2022	98804.6082	896.0650088
Santiago	Fogo	Cape Verde	113	10'	49000	2022	49401.8	448.0279327
Santiago	Sao Nicolau	Cape Verde	220.4	40'	199282	2022	200916.112	1822.120459
Santiago	Sao Nicolau	Cape Verde	220.4	20'	102015	2022	102851.523	932.7667256
Santiago	Sao Nicolau	Cape Verde	220.4	10'	51007	2022	51425.2574	466.3787911
Santiago	Boavista	Cape Verde	153.7	40'	199282	2022	200916.112	1822.120459
Santiago	Boavista	Cape Verde	153.7	20'	102015	2022	102851.523	932.7667256
Santiago	Boavista	Cape Verde	153.7	10'	51007	2022	51425.2574	466.3787911
Santiago	Sao Vicente	Cape Verde	296.3	40'	199282	2022	200916.112	1822.120459
Santiago	Sao Vicente	Cape Verde	296.3	20'	102015	2022	102851.523	932.7667256
Santiago	Sao Vicente	Cape Verde	296.3	10'	51007	2022	51425.2574	466.3787911

For Containers								
From	To	Country	Distance (km)	Type	Cost_country_currency /container	Year_of_country_currency	cost in 2023	Cost (Euro2023/container)
Natovi	Buresala	Fiji	16.471	40'	1960	2015	2318.15526	946.1858218
Natovi	Buresala	Fiji	16.471	20'	1120	2015	1324.66015	540.6776125
Natovi	Savusavu	Fiji	128.444	40'	1800	2015	2128.9181	868.9461629
Natovi	Savusavu	Fiji	128.444	20'	1350	2015	1596.68857	651.7096222
Natovi	Nabouwalu	Fiji	78.219	40'	3360	2015	3973.98045	1622.032837
Natovi	Nabouwalu	Fiji	78.219	20'	2520	2015	2980.48534	1216.524628
Savusavu	Taveuni	Fiji	89.195	40'	2732	2015	3231.22458	1318.867176
Savusavu	Taveuni	Fiji	89.195	20'	1751	2015	2070.96422	845.2915174
Koro	Taveuni	Fiji	92.089	40'	2769	2015	3274.98568	1336.728847
Koro	Taveuni	Fiji	92.089	20'	1775	2015	2099.34979	856.8774662
Koro	Savusavu	Fiji	63.215	40'	2675	2015	3163.80884	1291.350548
Koro	Savusavu	Fiji	63.215	20'	1715	2015	2028.38586	827.9125941
Suva	Taveuni	Fiji	259.731	40'	3174	2015	3753.99225	1532.241734
Suva	Taveuni	Fiji	259.731	20'	2035	2015	2406.86018	982.3919119
Suva	Savusavu	Fiji	209.086	40'	3055	2015	3613.24711	1474.794738
Suva	Savusavu	Fiji	209.086	20'	1958	2015	2315.7898	945.2203261

Source: Compiled from [67,125]

Appendix 7: Eligibility Matrixes & additional route constraints input matrixes

Note that 1 means eligible while 0 means ineligible. For pipelines:

INDEX	Santo Antao	Sao Vicente	Sao Nicolau	Sal	Boa Vista	Maio	Santiago	Fogo	Brava
Santo Antao	0	1	1	1	1	1	1	1	1
Sao Vicente	1	0	1	1	1	1	1	1	1
Sao Nicolau	1	1	0	1	1	1	1	1	1
Sal	1	1	1	0	1	1	1	1	1
Boa Vista	1	1	1	1	0	1	1	1	1
Maio	1	1	1	1	1	0	1	1	1
Santiago	1	1	1	1	1	1	0	1	1
Fogo	1	1	1	1	1	1	1	0	1
Brava	1	1	1	1	1	1	1	1	0

For sub-sea power cables:

INDEX	Santo Antao	Sao Vicente	Sao Nicolau	Sal	Boa Vista	Maio	Santiago	Fogo	Brava
Santo Antao	0	1	1	1	1	0	0	0	0
Sao Vicente	1	0	1	1	1	0	0	0	0
Sao Nicolau	1	1	0	1	1	0	0	0	0
Sal	1	1	1	0	1	0	0	0	0
Boa Vista	1	1	1	1	0	1	1	1	1
Maio	0	0	0	0	1	0	1	1	1
Santiago	0	0	0	0	1	1	0	1	1
Fogo	0	0	0	0	1	1	1	0	1
Brava	0	0	0	0	1	1	1	1	0

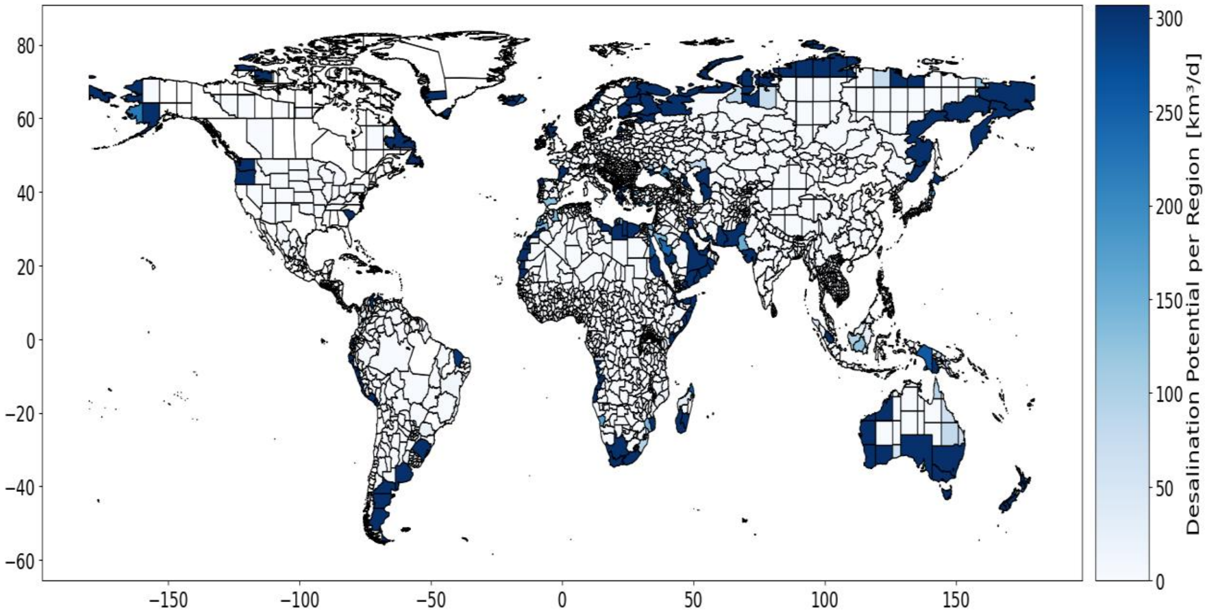
The monthly trip frequency considered:

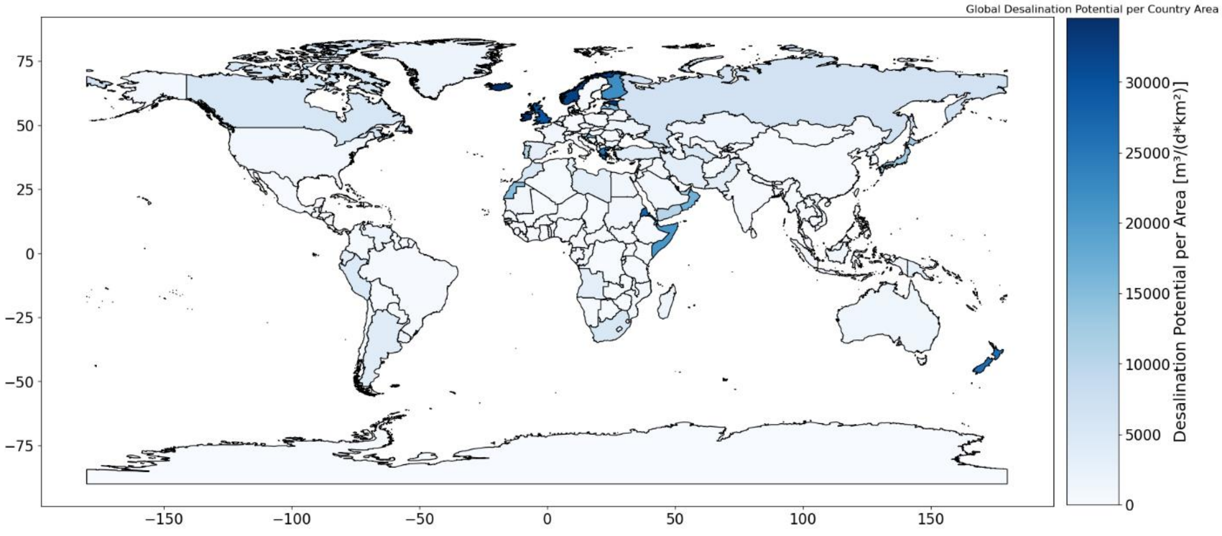
index	Santo Antao	Sao Vicente	Sao Nicolau	Sal	Boa Vista	Maio	Santiago	Fogo	Brava
Santo Antao	0	56	0	0	0	0	0	0	0
Sao Vicente	56	0	10	0	0	0	8	0	0
Sao Nicolau	0	10	0	8	0	0	8	0	0
Sal	0	0	8	0	8	0	0	0	0
Boa Vista	0	0	0	8	0	0	8	0	0
Maio	0	0	0	0	0	0	12	0	0
Santiago	0	8	8	0	8	12	0	12	0
Fogo	0	0	0	0	0	0	12	0	12
Brava	0	0	0	0	0	0	0	12	0

The maximum number of trucks per month:

	Santo Antao	Sao Vicente	Sao Nicolau	Sal	Boa Vista	Maio	Santiago	Fogo	Brava
index									
Santo Antao	0	13	0	0	0	0	0	0	0
Sao Vicente	13	0	9	0	0	0	9	0	0
Sao Nicolau	0	9	0	9	0	0	9	0	0
Sal	0	0	9	0	9	0	0	0	0
Boa Vista	0	0	0	9	0	0	9	0	0
Maio	0	0	0	0	0	0	7	0	0
Santiago	0	9	9	0	9	7	0	7	0
Fogo	0	0	0	0	0	0	7	0	7
Brava	0	0	0	0	0	0	0	7	0

Appendix 8: Global desalination potential





Appendix 9: Objective function of FINE

FINE’s objective function is to minimize the sum of the total annual cost (TAC) of all components [72] and it is done by the following formula:

$$z^* = \min \sum_{comp\in\mathcal{C}} \sum_{loc\in\mathcal{L}^{comp}} \left(TAC_{loc}^{comp,cap} + TAC_{loc}^{comp,bin} + TAC_{loc}^{comp,op}\right)$$

In details**:**

$$\begin{aligned} z^* = \min \quad & \sum_{comp\in\mathcal{C}} \sum_{loc\in\mathcal{L}^{comp}} \left[\mathrm{F}_{loc}^{comp,cap} \cdot \left(\frac{\mathrm{investPerCap}_{loc}^{comp}}{\mathrm{CCF}_{loc}^{comp}} + \mathrm{opexPerCap}_{loc}^{comp}\right) \cdot cap_{loc}^{comp} \right. \\ & + \mathrm{F}_{loc}^{comp,bin} \cdot \left(\frac{\mathrm{investIfBuilt}_{loc}^{comp}}{CCF_{loc}^{comp}} + \mathrm{opexIfBuilt}_{loc}^{comp}\right) \cdot bin_{loc}^{comp} \\ & \left. + \left(\sum_{(p,t)\in\mathcal{P}\times\mathcal{T}} \sum_{\mathrm{opType}\in\mathcal{O}^{comp}} \mathrm{factorPerOp}_{loc}^{comp,opType} \cdot op_{loc,p,t}^{comp,opType} \cdot \frac{\mathrm{freq(p)}}{\tau^{years}}\right)\right] \end{aligned}$$

Once the input data is processed, the output of FINE includes TAC and investment of individual components, and/or the complete system, optimal capacities, hourly operational time series as well as plots concerning technology distribution and/or operation.

Appendix 10: Max capacity of existing power plants (MW)

Islands	Power Plants
Santo Antao	6.6
Sao Vicente	24.443
Sao Nicolau	4.42
Sal	18.54
Boa Vista	18.54
Maio	3.272
Santiago	79.142
Fogo	7.84
Brava	1.704