Optimal Configurations of Hybrid Renewable Energy Systems for Islands’ Energy Transition

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Optimal Configurations of Hybrid Renewable Energy Systems for Islands’ Energy Transition

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“Unless someone like you cares a whole awful lot,
Nothing is going to get better.
It’s not.”

- Dr. Seuss
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Finally, I would like to thank all the dreamers, thinkers and speculative philosophers I have met throughout my life, you all have a place in my heart; without you, my journey until here would not have been as enjoyable!

Now that this chapter is finished, on to the next one!

Jorge Fuchs Illoldi
October 2017
The world’s greenhouse gas emissions (primarily CO₂) have steadily increased as a result of the continued use of fossil fuels, causing climate change. Nevertheless, sustainable energy technologies implementation has increased steadily in the last decade as society attempts to transition to a sustainable, zero emission energy system. The consequences of climate change are plentiful and represent a huge challenge for the whole world, but for islands they represent a threat to their existence.

Islands rely on expensive imported fossil fuels for their energy supply, which not only contribute to climate change but represent a threat in terms of energy security. Nonetheless, they also have all the possibilities and incentives to become the world’s leading example on how to transition to sustainable energy systems. Generally, islands possess abundant renewable resources which can be exploited and have smaller (less complex) systems compared to mainland grids. Moreover, many islands have set targets for renewable energy integration. However, in order for a transition to a sustainable energy system to happen there are multiple challenges that need to be overcome. One of the most important is lack of knowledge on the global potential of various sustainable energy technologies and their potential impact on the energy system.

This thesis has investigated the potential effect that different conditions on power supply and electricity demand have on the cost-optimal configurations of hybrid renewable energy systems of islands. This was done by studying the roles of various generating technologies (PV, Wind, OTEC, tidal, WEC and biodiesel) on the supply side and scenarios regarding residential heat electrification and commercial cooling on the demand side. For this purpose, a general model was developed on which the proposed loads and the power system performance was evaluated. The system was optimized using multiobjective optimization with economic (LCOE) and renewable integration (coverage) objective functions by means of a non dominated sorting genetic algorithm (NSGA-II). Eleven islands spread throughout the world were used as case studies.

It was found that there is a strong business case for renewable energy on islands as LCOE decreases with their implementation. Mature technologies such as wind and PV often have an important role in the first stages of the transition with wind always being part of the cost-optimal configurations and favoured in the 0%-50% range of renewable integration and PV starting at 30% and up to 70%. At higher levels their deployment is limited by the cost of storage and required overcapacities. Ocean technologies, particularly OTEC due to its baseload power generation, proved to have a potential role at higher integration shares starting in the range of 60% - 80%, greatly reducing energy curtailment. Finally, biodiesel was found to be important at the last stages limiting the cost and reducing overcapacity of generating and storage technologies.

On the demand scenarios, it was found that heat electrification has an impact on the total installed capacity but not on the relative composition of optimal configurations. Finally, complementary technologies for OTEC as SWAC can have a role when cooling loads are considered, nevertheless, costs need to be reduced as the cooling profile has a direct correlation with PV power, being more cost effective to let electricity increase by supplying cooling power with AC units and supplying the extra power with PV.

This study provides a powerful tool which is suitable to perform global assessments of the potential of various renewable energy technologies. The insights found on the specific roles of technologies can help as a support for establishing feasible targets and developing roadmaps, aiding in the transition to a sustainable energy system.
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Chapter 1

Introduction

Despite the multiple warnings (and efforts) made throughout the last 50 years, the world’s greenhouse gas emissions (primarily CO$_2$) have steadily increased as a result of the continued use of fossil fuels causing climate change. Moreover, energy consumption has followed the same trend and is expected to increase by 48% by 2040 [1] and needless to say, most of the world’s electricity systems are fossil fuel based. Nevertheless, sustainable energy technologies implementation has increased steadily in the last decade as society attempts to transition to a sustainable, zero emission energy system.

The consequences of climate change are plentiful and represent a huge challenge for the whole world, but for islands they represent a threat to their existence. A rise in sea level can cause the flooding of complete islands and extreme weather events such as hurricanes have the power to destroy a country. The latest example is hurricane Maria in the Caribbean, which collapsed the complete electricity system of Puerto Rico on September 2017.

Ironically, islands rely on expensive imported fossil fuels for their energy supply, which not only contribute to climate change but represent a threat in terms of energy security. Nonetheless, they also have all the possibilities and incentives to become the world’s leading example on how to transition to sustainable energy systems. Islands generally possess abundant renewable resources which can be exploited and have smaller (less complex) systems compared to mainland grids. Moreover, many islands have set targets for renewable energy integration.

However, in order for a transition to a sustainable energy system to happen, there are multiple challenges that need to be overcome. One of the most important is a lack of knowledge on the global potential of various sustainable energy technologies and their potential impact on the energy system. Islands often rely on foreign aid to finance renewable energy projects and there has been discussion on whether the targets set by some governments are congruent with the resources available, as high targets can be used to gain leverage on global climate change discussions which can hinder the funding availability.[2] Furthermore, transfer of solutions from one island to similar locations can facilitate the transition, nevertheless, once again, information on possible similarities between islands on different locations is needed.[3] Finally, energy transition is a slow process and technologies not commercially available yet could play an important future role, having an impact on transition strategies and roadmaps. In order to consider them, information is also needed.
Chapter 1. Introduction

1.0.1 Research project motivation

An increasing number of studies and modeling tools have been done to aid governments in the energy transition. Often, these studies focus on specific case studies being location specific and the modeling tools for renewable energy systems considered only take into account those technologies that are mature, primarily PV and wind, as will be seen in the upcoming literature review. At TU Delft, three students working previously on islands under Kornelis Blok have investigated and developed general models on how a cost optimal system should look like for various penetration levels and how newer ocean energy technologies (not yet fully commercial) can play a role in higher penetrations of renewable energy systems. So far, ocean technologies have been assessed for 2 islands, and PV, wind and storage for 6. Additionally, another research was carried on a case study on the role of electric vehicles and charging strategies as enablers for high penetration renewable energy systems.

However, these models have been evaluated for a small sample of islands and their ability to cope with location specific characteristics and future developments have not been fully tested. For instance, there is a trend of electrifying vehicles and appliances to increase their efficiency, decrease their carbon footprint and be compatible with the future renewable power system. However, it has not been studied how the adoption of these technologies affect the optimal energy generation mix. Thus, there is a knowledge gap in understanding how these developments could affect an islands’ energy system configuration.

1.0.2 Research Objective

The main goal of this thesis is assist in the transition to a renewable power sector by assessing the potential of renewable energy on islands. This will be done by determining cost-optimal energy configurations for selected islands at different renewable energy penetration levels and evaluating the impact that different conditions of demand and supply have on the power generation configuration. Additionally, it is of interest to develop a model describing an island power system which can be general enough to be utilized in various locations and ultimately allow to perform a global assessment.

1.0.3 Research Questions

How do the cost-optimal configuration of an island energy system, moving towards 100 % renewable energy, are affected by different conditions of energy demand and supply?

Sub-questions

- How is energy used in islands? How much is used as electricity, heat and transportation fuels? Which sectors could have an impact on the electricity demand if electrified?
- What is the role of ocean technologies in the transition to renewable energy systems on islands? What are their specific roles under the aforementioned conditions?
- What is Ocean Thermal Energy Conversion’s (OTEC) potential regarding service sector cooling (via seawater air conditioning (SWAC)) and what effect could it have on the electricity demand and the system’s configuration?
• How does the electrification of the residential heat of tropical islands affect the system's configuration?
• How does biodiesel generation affect the system's configuration?

1.0.4 Research Approach

The main research question will be answered by means of a model that determines the cost-optimal configuration for a given island provided the necessary input data. The model will be based on the one proposed by van Velzen and should be able to evaluate different scenarios regarding demand and supply and also should be able to be applied to various island case-studies.

The following research approach is proposed. First, an analysis on the energy use on islands will be made to understand how energy is used and to identify and select possible electrification/demand scenarios. Once the scenarios are selected, approaches on their modeling will be reviewed. Taking into account the scenarios and the technologies to be considered, islands selection for case studies will be performed and data acquisition will be carried out. The insular power system model coupled with a genetic algorithm will be developed and finally the proposed scenarios will be evaluated.

1.0.4.1 Thesis scope and boundaries

This thesis aims to assess the potential of renewable energy on islands by determining the cost-optimal configurations of hybrid renewable energy systems composed of conventional generation, renewable energy technologies and storage. Thus, the research intends to provide insight on the potential roles of the considered technologies to support governments in the energy transition as opposed to a more detailed modeling for specific project development.

Moreover, while this thesis project will study the energy use in islands, the model will only consider the power sector. As a consequence, other elements of the islands’ energy system will only be addressed when they have an influence on the electricity demand. (i.e. the proposed demand scenarios of tropical residential heat electrification conformed by water heating and cooking and commercial cooling supply by means of seawater air conditioning (SWAC) coupled with ocean thermal energy conversion (OTEC)).

Finally, this thesis can be seen as a continuation of the work previously developed by the students of professor Blok, and based on their work and recommendations, the generating technologies to be included in the model are: photovoltaic panels (PV), wind turbines, wave energy converters (WEC), OTEC, tidal turbines, conventional generation (fossil fuel based), battery storage and biodiesel based generation.

1.0.5 Thesis outline

This thesis is comprised by 10 chapters. A brief overview of each one will be provided below.
Chapter 2 gives a review on the relevant literature concerning hybrid renewable energy systems modeling, domestic hot water and cooking demand estimation, space cooling demand estimation and the positioning and contribution of this thesis.

Chapter 3 provides an analysis on how energy is used on islands using the world energy balances of the IEA, from where potential demand scenarios are identified. Moreover, a selection of the demand scenarios is made and information on how those scenarios can be modeled is provided.

Chapter 4 gives a general overview of the island context and introduces the selected islands for the case studies. Finally, it provides information of the meteorological and electric demand data needed for the model evaluation.

Chapter 5 describes the model developed to describe insular power systems. First, some background information on island’s electricity systems and the relevant generating and storage technologies is provided. Then, a general description of the model and of each technology with the most relevant assumptions is given. Finally, the control logic and how the demand was modified for each scenario is discussed.

Chapter 6 deals with the optimization technique used and the optimization problem formulation, stating the objective functions and constraints considered. Additionally, costs regarding generating technologies and fossil fuels are provided.

Chapter 7 presents the results of the different cases and technology scenarios on the optimal configurations for the island case studies.

Chapter 8 shows the sensibility of the model results to the variation of the input parameters.

Chapter 9 discusses the results obtained from the evaluation of the cases and scenarios and from the sensitivity analysis. Additionally, the research approach is discussed and a methodology is proposed. Finally, a discussion on the model and its limitations is provided.

Chapter 10 presents the final conclusions of the thesis project and provides recommendations for future research.
Chapter 2

Literature Review

A literature review was performed to gather relevant information and knowledge on the topic concerning this thesis and to track recent developments on the field. There are various areas encompassed on this thesis project with multiple relevant topics needed for its development and context. Within the island group under the supervision of professor Blok, past work has been developed on the topic with extensive literature review on the topics of HRES modeling and optimization [4, 5], ocean technologies and transition frameworks [5] and battery services and electric vehicles [6]. This literature review aims to complement the research performed previously on hybrid renewable energy systems for islands and dive into models and techniques for domestic hot water, cooking and space cooling demand estimation. In the following sections the most relevant papers will be addressed. The literature review overview is shown in Table 2.1.

2.1 Hybrid renewable energy systems for Islands

HRES for islands is a very broad topic, and for the purpose of this work, it was preferred to restrict it to modeling and optimization techniques, island system characteristics and barriers and studies regarding their possibilities in the energy transition. It was of particular interest to focus on a general more global approach rather than on specific case studies as the one of the goals of this project is to provide insights on the potentials of various technologies. The most relevant papers studies are discussed in the following paragraphs.

Bleichinger et al. (2016) [7] used a GIS to identify all islands with a population between 0-100000 people using georeferenced datasets. (population density, economic activities, island remoteness, PV and wind potential). Assessed the potential of the 1800 identified islands via hourly simulations. The model included diesel generators, battery storage, wind and PV. The control of the system took into account stability requirements as spinning reserves and minimal loading of the diesel generators. The model was used to find the cost-optimal system configuration minimizing the LCOE and the capital recovery factor. Additionally, they estimated the diesel price on each island taking into account the island remoteness and current price of diesel. They calculated the diesel LCOE for each group of islands to be between 37.2 USDct/kWh in the Caribbean to 45.1 in the Pacific ocean. Moreover, they found that the highest renewable energy share can be attained in the Caribbean (64%) and the lowest in the Indian ocean (39.8%), with the LCOE of the hybrid system being between 27.9 USDct/kWh and 35.9 USDct/kWh. Finally, they provided insights on the (ranked) barriers USDct/kWh for renewable energy adoption on islands.
<table>
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<th>Author</th>
<th>Year</th>
<th>Modeling</th>
<th>Optimization</th>
<th>HRES on islands</th>
<th>System characteristics</th>
<th>Transition &amp; barriers</th>
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</table>
2.1. Hybrid renewable energy systems for Islands

Gioutsos (2016) [4] studied the cost optimal configurations of HRES on 6 islands considering PV, Wind and diesel generation with pumped hydro and batteries as storage. He found that LCOE decrease considerably with renewable energy penetration of 40%-70%, with wind technology being the most important. Additionally, he found that pumped hydro was preferred over batteries whenever possible on penetrations greater than 70%, however if the price of batteries decrease by 50% this storage technology is expected to be more favorable. Finally, he identified as a no-regret measure for islands to invest in wind generation up to a 20% integration and wait on battery storage decisions once a higher integration is reached (and battery costs reduced).

van Velzen (2017) [5] studied the potential of ocean technologies in a HRES by performing 2 case studies on Aruba and Shetland using a non-dominated sorting genetic algorithm (NSGA II) and optimizing the configurations on LCOE and integration of renewable energy. She found that commercially mature technologies (PV and wind) dominate the renewable installed capacities as they have the lowest cost. Additionally, she found that ocean technologies are relevant at higher renewable integration as they allow the generation to be more evenly spread. The consequence is a lesser need for storage energy and a decrease in dumped energy. Finally, she found that the role of ocean technologies are highly dependent on the location, northern islands are more likely to adopt WEC and tidal whereas tropical islands show a clear preference toward OTEC.

Meschede et al. (2016) [3] aimed to classify the identified islands (population range of 0-3,500,000 and distance to mainland of 10 km) to facilitate technology and knowledge transfer to accelerate energy transition. In the study, 1087 islands were identified using a GIS and georeferenced data. Based on their meteorological, socio-economic, and physical characteristics, the islands were grouped in 8 climatological clusters and 8 socio-economic/island physical characteristic clusters. It was found that climatological clusters showed stronger structures than the socio-economical ones. Additionally, it was found that socio-economical clusters could be either regional or global. Moreover, 10 main combined clusters were identified using the number of islands and people as criteria. The proposed clusters as well as their possibilities of technology transfer were validated using the Canary Islands as case study. They conclude that the climate cluster analysis allows to estimate the “suitability” of generating technologies while the socio-economic can be a first approximation to the potential. Nevertheless, they argue that it only can be seen as a baseline as further analysis and data on energy consumption is needed.

Neves et al. (2014) [11] performed a review on case studies of HRES on islands and remote villages. For their review, they considered places with a population up to 10,000, but found that most of the studies were performed in places with a population of less than 10,000 and mainly in Europe. They found that for islands the most common configuration is PV, Wind and diesel generation with a renewable energy penetration ranging from 25 to 100%, but note that all stand-alone systems are not able to integrate more than 50% renewable if the population is higher than 5,000 due to storage costs. Finally, they propose a framework for reporting HRES projects that allows the comparison between projects.

Notton et al. (2015) [15] describe the characteristics of insular systems putting special attention on the challenges posed by renewable energy integration on the islands’ grids. They discuss stability issues present on the electricity system and the main differences with mainland grids, being the unit peak power to mean demand ration (must not exceed 0.25), the small amount of units and costly and slow startup times of generators and high electricity prices (0.12-0.31€/kWh compared to regulated price of 0.0517€). Furthermore, they address the challenges represented by the innate variability of PV and wind generation and conclude that although islands have all the incentives to transition to renewable systems, developments in renewable generation forecast, smart grids and storage need to be done.
Dornan (2015) [2] looked into the development of renewable energy in SIDS of the Pacific. Risk mitigation is identified as the main reason for transitioning to renewable energy systems. He analyses from a public policy perspective specifically the targets proposed by SIDS and identifies the main barriers. Out of which, the most important are little private sector investment, lack of regulatory framework, inconsistency of lofty targets and high dependency on foreign aid. In these last two regards, he argues that more information on the real potential of renewable energy is needed to set congruent targets that can lead to more involvement of technical organizations for implementation. Furthermore, he raises the question whether foreign aid should be used for renewable integration to the electric system instead of poverty alleviating activities such as rural electrification. He concludes that alignment between targets and energy organizations is required for an effective planning of the energy sector.

Betzold (2016) [16] analyzed the development of aid for renewable energy in Pacific SIDS using data form the OECD from 1990 to 2012. It was found that there has been a shift in recent years towards renewable energy projects, being hydro and solar power the most important technologies. Additionally, it was found that grid projects were preferred over off-grid projects, benefiting the population who is generally in a better economic situation. Finally it was found that “hardware” (equipment, infrastructure) was heavily preferred over “software” (capacity building, training and policy making) projects. Betzold concludes that a shift in donor thinking has occurred and is expected to continue in the coming years.

Osorio et al. (2016) [17] explored the possibilities of deep ocean water (DOW) to contribute to the development of islands. They came with the concept of ocean technology ecopark as a proposal for supplying the island of San Andres with electricity, fresh water, air conditioning (SWAC) and opportunity of development of other industries. Additionally, they identified the main barriers for the deployment of OTEC technology and DOW technologies and stated a roadmap for the ecopark development. They analyze the feasibility of the synergy between DOW technologies and state the possibility of implementing SWAC independently or in cascade with OTEC.

Al-falahi et al. (2017) [12] provide a comprehensive review of single and hybrid size optimization approaches. They reviewed over 150 papers and provide a complete insight on how sizing and modeling of HRES in islands and remote locations is done. They start by providing an overview on the various system configurations of electricity systems for islands investigated in the literature and conclude that solar, wind and storage coupled or not with conventional generator are the most studied topology. Additionally, they mention that the inclusion of other renewable energy technologies have been explored in a stand-alone system and that only few studies have dived into the possibilities of coupling diverse renewable, storage and conventional sources, mainly due to the high initial costs. In the article, they also discuss about the importance of meteorological and demand data for the sizing results. They discuss various articles on which different forecasting and estimation approaches are carried out. Furthermore, they provide an overview on the objective functions used for HRES sizing. They differentiate between 4 main categories: economical, reliability, environmental and social; with most of the studies reviewed focusing on the first two. The main part of the paper however, is the review and comparison of size optimization techniques which they identify to be classical techniques (iterative, LP, MILP), artificial techniques (GA, PSO, SA, ANN-GA-MCS, etc) and software tools (HOMER, iHOGA). Furthermore they differentiate between studies using single algorithms and hybrid algorithms. The main findings and conclusions of the article are:

- There are few studies considering social assessments, however social factors as social acceptance are likely to influence the system configuration.
• The use of classical optimization methods have decreased and there is a preference for artificial methods due to their ability to provide a set of optimal results and search for global optima.

• Particle Swarm Optimization (PSO) and Genetic Algorithms (GA) are very popular. Nevertheless, hybrid algorithms have proved to increase convergence and reduce computation time.

• For cases with triple objective optimization, NSGA-II algorithm was the most common.

• HOMER is widely used for standalone system design but is limited to single objective optimization (minimizing NPC).

• iHOGA is a software less used based on GA and that allows in its pro version to perform multiobjective optimization.

2.2 Heating and cooling demand estimation

It has been found that most of the HRES on islands research focus on electricity consumption. Additionally, in the attempt to transition to a sustainable energy system and fight climate change, electrification has been acknowledged to present an opportunity as the electricity system can be more easily decarbonized. In the particular case of tropical islands, space heating is barely needed leaving hot water production and cooking as the main activities. Additionally, the warmer often humid climatological conditions make cooling demand a relevant end use. Thus, a focus was put on ways of synthesizing and estimating heating and cooling demands. The most relevant literature is described below.

Martínez-Gómez et al. (2016) [18] conducted a study in which a comparison between an LPG, electric and induction stove was made. They performed the comparison on 4 areas: energy consumption, gaseous emissions, organoleptic and physicochemical and microbiological. The study was performed by cooking a generic Ecuadorian dish and measuring the selected areas. They provide a detailed measurement of cooking times and energy consumption per stove per dish and found out that induction stoves can reduce considerably the energy consumption for cooking. They conclude that induction stoves have the best overall performance reducing the energy consumption and having more acceptance on the food cooked. Additionally, the electric based stoves do not emit noxious gases nor have a negative effect on the microbiological analysis.

Hager et al. (2013) [19] performed a review on the energy consumption during cooking. They discuss the various processes present while cooking as well as the different appliances efficiencies and energy sources. The main cooking appliances are stoves, ovens and microwaves with the former two having various energy sources as natural gas, LPG and electricity. They identified electric stoves as the most efficient (mature) technology for table top stoves. Additionally, they argue that consumer behavior has an important impact on the energy consumed as a study suggested that people not controlling cooking parameters can double the energy consumption. Additionally, they provide a detailed description of the energy needed to prepare specific dishes with various energy sources being electric stoves the technology with lower values. Finally they identified policies for reducing cooking energy to be consumer education, enhanced appliance efficiency and regulations on stand-by energy consumption.

Ferrantelli et al. (2016) [20] developed a domestic hot water consumption model for Finnish apartments by generating a structural dataset (derived from real data) which can be adjusted to
a specific time period using structural coefficients derived from fitting the model to data. They validated their model comparing it with two different Finnish datasets with low overall water consumption error. (Calculated 45.56 l/p and the real value was 45.065 l/p). They conclude that the model can help create new energy consumption profiles but that it is restricted to places where the population have a similar behaviour.

Blökker et al. (2010) [21] created a water demand end use model based on statistical information on appliances and users. Their model simulates the water usage by determining the water consumption (simulated as pulses) for 8 end uses (hot and cold water), various users (teens, children and adults) and estimating frequency of use, intensity and duration of each of the end uses (e.g. shower has a frequency of 0.7 per day and a duration of 8.5 min with an intensity of 0.142 l/min). Various types of distributions are proposed including Poisson, negative binomial and lognormal to describe the different components of the model. They conclude that the simulated results are in agreement with the measured patterns, however discussing that the model can be improved by adding more water uses, better estimation of the intensity, duration and probability.

Widen et al. (2009) [22] proposed a methodology for constructing household electricity and hot water profiles using time-use data. In their model they relate activities reported by the respondents to end uses and estimate time and energy consumption for that end use (e.g. 2.1 kWh/5 min for shower). They compare the simulated profiles to real data and conclude that the model can generate realistic electricity demands for individual households and that the agreement between measured and simulated profiles is better for electricity than hot water. They also conclude that hot water use is highly influenced by showering habits and appliances and that although magnitude diverges, the model represents the load pattern adequately for hot water use.

McNeill and Letschert (2008) [24] studied the effect that adoption of air conditioning can have on the energy consumption in developing countries. To do so, they modeled the air conditioning ownership as a combination of two variables: climate maximum saturation and availability. The former is the result of the climate of the place and the latter is related to the effect of income on air conditioning adoption. Finally, they developed scenarios on energy efficiency to determine the total energy consumption in the future.

Isaac and Van Vuuren (2009) [25] modeled the evolution of heating and air conditioning demand in the residential sector in the 21st century taking into account climate change. To do that, they used models based on degree days, floor area an availability (both functions of income), saturation (effect of climate) and efficiency. They found out that for their reference scenario there is not an overall increase in energy consumption. Nevertheless, there are important effects regionally and for the end uses. They conclude that heating demand is expected to decrease by 30% and cooling demand increase by 70% (mainly in developing countries specially in Asia) and due to the fact that electricity generation has a higher emission factor, CO2 emissions are expected to rise as well.

Jakubcijonis and Carlsson (2017) [26] performed an estimation of the cooling potential in Europe. They used georreferenced data from United States to establish a relationship between electricity consumption and CDD and calculated the energy consumption for various countries of Europe. The estimation results were compared to other cooling demands reported (e.g. estimated value for Cyprus 75.8 kWh/y, reported values 50-83 kWh/y). Finally they calculated the impact that the extra cooling load would have on the electricity system estimating an increase needed of 79.6 GW.
2.3 Thesis contribution

Werner (2016) [27] estimated the space cooling demands for Europe (service and residential sector) based on real cooling loads data. The study was done within the Stratego project and had the objective of determining the cooling demands for planning and modeling purposes. The cooling demands were estimated based on the European cooling index (ECI) which takes into account the CDD and heat resistances of buildings, specific space cooling demands, building floor areas and saturation rates, considering a SEER of 3.1 and that residential cooling demand is 45% of the service cooling demand. The estimation was performed for 28 European countries and benchmarked against other studies. He concludes that the estimations proposed are lower than other estimations mainly due to the sources and assumptions made. Additionally, he states that due to the lack of information on cooling demand, the estimations can be improved by using more samples and having better quality information on the service area per country and ECI values for more places other than the capital cities.

2.3 Thesis contribution

From the literature review and past work within the research group it was found that although various studies have addressed the optimal configuration of HRES in islands, there are few studies performing a global assessment, i.e. considering multiple locations and evaluating the potential of various resources. Additionally, there has yet to be done a study considering electrification scenarios that could occur in the near future while transitioning to a sustainable energy system, particularly for uses where where appliances are readily available for applications such as domestic hot water, cooking and space cooling. Additionally, it was found that there is lack of information on global cooling demands particularly for island countries. Finally, there is still a knowledge gap in the potential contribution of ocean technologies to the energy transition. Therefore, this thesis is a study that aims to contribute directly to these topics.
Chapter 3

Energy use in Islands

In general, energy is consumed in diverse forms mainly as electricity, heat or liquid fuels. Many of the studies carried out in the literature [8, 7] as well as in TU Delft’s Island Group [4, 5] focus on improving islands’ electricity supply by using renewable energy for power generation. The results of these studies show potential benefits such as increasing energy security (independence from imported fuels), reducing the carbon footprint and reducing the cost of electricity, are very relevant. However, they are limited because the energy use considered, the electricity consumption, is just a fraction of the total energy consumed. Specifically, the energy use on islands has not been studied in the literature, thus the full impact of addressing only the electricity consumption cannot be completely evaluated as it is not known the fraction of the total energy used it represents.

This chapter intends to address the energy use on islands and provide an insight on the usage of energy, providing relevant information on how and where energy is used on islands. Specifically the energy self sufficiency, the sources predominantly used for power generation, the quality of the energy distribution and the relative composition of energy consumption is to be addressed.

3.1 Overall Energy Use on Islands

Data acquisition

To perform the analysis on energy use, the World Energy Balances of 2016 published by the International Energy Agency (IEA) [28] was used. The world Energy Balances is a report published annually in which the energy balances and flows of different countries are shown. The information covers energy supply, transformation and consumption as well as different energy sources such as diverse petrochemicals, renewables and nuclear; thus, it provides relevant information to perform an analysis on how the energy is used.

From the total of 170 countries included on the database, only 14 island countries with a population of maximum 12,000,000 people were identified with complete information and are shown in Table 3.1. These countries are distributed throughout the globe, nevertheless it is important to point out that 6 out of 14 are located in the Caribbean as can be seen in Fig 3.1. Moreover, the orange islands indicated in Figure 3.1 (Ireland, Malta and Bahrain) are not grid disconnected,
which means that they are coupled via submarine cables with larger electricity systems. However, because this analysis focuses on energy rather than power generation self-sufficiency, it is therefore considered that even grid connected systems can provide useful insights on how the energy is used.

Finally, although the report contains information up to 2015, it should be noted that for the selected countries the most recent year for which the complete information was available was 2014.

Table 3.1: Island countries’ overview from 2014 considered for the Energy Use analysis derived from IEA’s 2016 World Energy Balances. [28]

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<td>0.41</td>
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<td>0.04</td>
<td>5,725</td>
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<tr>
<td>Jamaica</td>
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<td>0.15</td>
<td>1,110</td>
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<td>Malta</td>
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<td>5,012</td>
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<tr>
<td>Mauritius</td>
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<td>0.07</td>
<td>2,182</td>
<td>20</td>
</tr>
<tr>
<td>New Zealand</td>
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<td>36,338</td>
<td>0.09</td>
<td>9,131</td>
<td>79</td>
</tr>
<tr>
<td>Trinidad and Tobago</td>
<td>1.35</td>
<td>16,207</td>
<td>0.63</td>
<td>7,137</td>
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</tr>
</tbody>
</table>
3.1. Overall Energy Use on Islands

Energy self sufficiency

Self sufficiency is an important parameter particularly because it provides an idea of the energetic vulnerability of a country. It is a measure of the dependence a country has on external parties to satisfy its energy needs, which could translate in turn, into economic freedom and sovereignty.

Of the 14 countries analyzed, only 3 proved to be self sufficient being Bahrain, Brunei and Trinidad and Tobago; particularly Bahrain and Brunei, which have important reserves of oil and natural gas.

On the other hand, when considering self sufficiency in terms of specific fossil fuel resources: coal, natural gas and oil, New Zealand was the sole country self sufficient in coal, 5 were in natural gas and 3 in oil. Moreover, 11 of the 14 countries were net energy importers in 2014, mainly of motor gasoline, diesel, oil and fuel oil.

Electricity generation

The International Energy Agency distinguishes 2 different electricity producers, one which its main purpose is purely electricity generation and another whose main activity is the production of heat and power (CHP). Additionally, the IEA distinguishes between main producer and auto-producer, the latter is that generator which uses the total or part of the electricity produced as an activity which supports its primary activity. An example would be a farmer who has a CHP plant to generate heat for its greenhouse and part of the electricity generated is consumed by him (and farming which is his activity) and the rest is sold. The electricity generation distribution of the studied islands is summarized in Figure 3.2.
As can be seen from the figure presented above, it can be stated that in general dedicated electricity plants are the most common type of electricity generation, however, independent auto-producer electricity plants may play an important role in smaller countries such as Curacao and Mauritius. Additionally, CHP plants does not represent yet an important fraction of the electricity generating capacity though in countries as Iceland, Ireland and New Zealand they comprise a fair amount of participation.

Additionally, when analyzing the fuel consumption and share of renewables in electricity generation on islands, most of the electricity generation on islands is based on fossil fuels, except from Iceland and New Zealand (Figure 3.3). Furthermore, it can be seen that the most used fuels are natural gas, fuel oil and diesel, being the last two the most imported fuels in most islands. This makes clear that implementing technologies that allow the island countries to produce its own electricity should be of high priority as it would allow them to increase their national security in terms of their electricity and overall energy system.
In terms of renewable energy production, renewable energy technologies are in general non-factors in current electricity systems, being Iceland the main exception producing 100% of its electricity from hydro and geothermal sources and New Zealand close to 80%. Finally, it is important to note that although renewable energies in general are not yet widespread implemented in island countries, it was found that technologies such as photovoltaics have a growing share of generation in the autoconsumer sector. Finally, it was also found that the there could be big transmission losses, particularly in Caribbean countries which can be as high as 60% in the specific case of Haiti, and generally over 15% with the exception of Dominican Republic. However, this transmission losses are not only due to the quality of the infrastructure but also due to electricity theft by irregular users. For the rest of the countries transmission losses was not an issue as it remained below 10% which is a typical number.

### Energy consumption

In general, energy is used as electricity, heat or fuels for transportation. The absolute amount of energy used by a country depends, among other factors, on the economic activities carried out by the country, its location and its economic development. Energy usage also scales up with population. For that reason, and because the main objective is to understand the typical energy use in islands, the energy use is analyzed not in absolute terms but relative within each country as can be seen in Figure 3.4.
Figure 3.4: Energy use for selected islands in 2014 derived from IEA’s 2016 World Energy Balances

The distribution of the use of energy varies depending on the country as expected. However, it can be seen that for most of the island countries analyzed, electricity currently represents less than 40% of the energy used. Energy related to transportation lies between 30-40% of the total, while heat varies greatly depending on the country, being higher for Caribbean countries, but generally in the range of 30-40%.

When taking a closer look at the energy use for transport, in all the countries over 90% of the energy is used by road vehicles. This is important because it is expected that in the future the automotive industry shifts from fuel based cars to electric vehicles [6]. Thus, part of the total amount of energy currently used in transportation (at least \( \frac{1}{3} \)) will become part of the electricity demand.

If the heat consumption is analyzed, it is found that most of the heat is used in industrial related activities and in the residential and commercial sectors as shown in figure 3.5a. It is important to point out the difference between heat demand and heat consumption. For example, in places where space cooling is required the amount of cooling energy needed represents part of the heat demand. Nevertheless, it is common practice to supply the required heat demand with air conditioners or heat pumps which function with electricity. As a consequence, to meet the heat demand, it is electricity that is consumed and not heat, unless there are district cooling services available which are able to provide heat directly. Places as Stockholm, Toronto and Honolulu have district cooling [29].

In the world energy balances, cooling is generally reflected in the electricity consumption and not on the heat consumption. For the case of heat pumps, the documentation of the world energy balances explicitly states that for the residential sector “heat pumps that are operated within the residential sector where the heat is not sold … (are considered under) electricity consumption (and) would appear as residential use.”
It is of particular interest the residential sector, as many of the islands are located near the tropics where space heating is rarely needed. As a result, and given that the space cooling demands are considered under electricity consumption, the heat consumption in the residential sector could be caused mainly by activities such as water heating and cooking. It could be the case as these island countries develop and attempt to transition to a sustainable energy system, that much of this heat consumption is electrified. The residential heat demand represents approximately 20% of the total heat consumption as shown in Figure 3.5a.

Finally, the average energy use for the studied island countries is presented in Figure 3.6. This general average energy use along with Figures 3.5a and 3.5b can be a useful as a first estimation for a typical energy use distribution on an island.
3.1.1 Demand scenario selection

From the energy use analysis on islands based on the World Energy Balances of the IEA, three possible demand scenarios which can have an impact on the electricity profile can be envisioned.

The first one is electrification of the residential heat consumption of tropical islands. As seen previously, heat consumption in the residential sector represents an important share of the total heat consumption of the island countries studied. That is true even for tropical islands who do not need space heating. Currently, there are technologies available which can provide the heat needed using electricity such as electric boilers, electric stoves and heat pumps.

The second possible scenario is the electrification of the transport sector. It was found that transportation fuels represent on average 30-40% of the total energy use and of the transport sector, most of it is used by road vehicles. The increasing adoption of electric vehicles allow to think that in the future this sector could be electrified, having important consequences on the electricity consumption. Additionally, electric vehicles could even have a role if integrated to the electricity system using V2G technology. [6]

The third scenario is regarding space cooling. Currently, the heat demand required by cooling is primarily supplied via electricity with air conditioners. Nevertheless, there are other possible sustainable ways to provide the cooling power required, for example using district cooling. Supplying the cooling loads with heat instead of electricity can allow to generate electricity savings decreasing electricity consumption. In particular, OTEC can have the possibility to supply cooling power coupling the normal OTEC plant with a seawater air conditioning (SWAC). [17] This technology however, is benefited from constant cooling demands, which are more likely to be present in the commercial sector.
For this thesis, the first and third scenarios proposed were selected to be studied. The second scenario however, was left out because to model and evaluate the effect of different electric vehicle charging technology and behavior on the electricity consumption and optimal configuration would require a complete thesis project.

### 3.2 Heat energy demand

Heat consumption represents a substantial share of the total energy use of islands, out of which the heat consumed on the residential and commercial sector represents over 50% of the total heat consumption. The US Energy Information Administration estimated that 20.9% of the total delivered energy consumed worldwide was on buildings, with electricity consumption accounting only for 53% for commercial buildings and 40% for residential buildings. These means that a very important fraction of the energy used is heat generated mainly by fossil fuel combustion. Additionally, the most important heat demands for the residential sector are heating, cooling, water heating and cooking while heating and cooling are the most important for the commercial sector. 

Electrification of heat has been ongoing for the past years and is expected to become even more important in the future. Supplying the heat demands with electricity instead of fossil fuels have various advantages such as higher efficiencies in heat generation with heat pumps and district heating being the most important examples and decarbonization of the energy system with the increasing participation of renewable energies in the electricity supply. Nevertheless, it also represents risks and challenges specially for places with limited electricity systems (such as islands) as an increase in the overall electricity consumption as well as in peak load can occur.

In particular for tropical islands, where space heating is rarely needed, the residential heat demand becomes mainly for water heating, cooking and cooling. Additionally, space cooling represents an important heat demand in the commercial sector. Thus, it is of interest to determine what would the impact on the electricity demand be if the former sector is electrified and the later supplied directly by cold seawater. To do so, the hourly heat demand profile for each application need to be assessed as each one of the end uses follow characteristic patterns.

#### 3.2.1 Residential Heat Demand: Hot Water and Cooking

The International Energy Agency through the energy balances generate useful information on the end uses of energy on different sectors including residential. Figure 3.7 shows the residential energy consumption by end use from 20 countries in 2010. The majority of the energy consumption is used for space heating, being water heating the second most energy consuming. Of the use shown in the figure, lightning, space cooling and appliances are mainly powered by electricity. Thus, heat consumption is conformed by space heating, water heating and cooking.

Considering the case of tropical islands, where space heating is not required in homes, the heat consumption becomes only water heating and cooking. Assuming the proportions are kept, then of the total heat consumption 80% is required for water heating and 20% for cooking. Nevertheless, it is important to mention that even though the values presented in Figure 3.7 are an average of 20 countries, the energy consumption can differ greatly between countries. For instance, in China only 33% of the energy was used for space heating while 25% was used for...
water heating and 12% for cooking and in India cooking was the main use representing a 63% and water heating accounted only for 10%. [32]

Figure 3.7: Residential consumption by end use for 20 countries in 2010.[32]

The energy consumption profile for each of the two identified uses is different as each activity is performed at different times of the day. When and how each activity is done depends on many factors such as the age, occupation, day, culture, among others. This fact makes it difficult to estimate with precision the exact added profile of all the people in a country. Various methods have been used to estimate load profiles for households using data collected of specific water consumption in a household or range of households [20, 23] or using more general time use surveys.[22]

To estimate the potential impact that electrification of domestic water heating and cooking can have in the electricity demand of an island, the time use survey approach was chosen. Time use surveys are studies carried out generally by governments where the respondents keep track of all the activities performed during the day in a diary, specifying start time, duration, end time, simultaneous activities, among other information. The information of the diaries are then coded and grouped under various categories for their analysis. These surveys provide information of the general behavior of the population, giving valuable insight on the preferred times to carry specific activities. Unfortunately, these studies are not performed in all countries, and none was found for the islands studied in this thesis. Thus, information of the 2015 American Time Use Survey (ATUS) of the United States performed by the Bureau of Labor Statistics is used to determine the hourly probability of hot water use and cooking. The underlying assumption is that the behavior of US citizens is representative of the behavior of people on islands.

Domestic Hot Water

Hot water is used in various activities inside a household such as showering, washing and cooking. Typically, washing machines and dish washers are fed with cold water and heated within the machine using electricity. [22] Hot water for cooking usually is heated to boiling point in the stove or with a kettle, leaving showering as the most important activity for hot water consumption. Thus, the hot water demand can be estimated based on the showering behavior. The activity “Washing, dressing and grooming oneself” of the ATUS groups various activities regarding personal care including bathing/showering. Nevertheless, it also groups other activities such as
grooming, brushing hair, washing face, washing hands, to name a few. This is a relevant fact because the reported duration of the general activity cannot be directly related to the length of the showering time. Additionally, short duration activities (less than 5 minutes) would rarely involve showering and more likely would be an activity such as “getting dressed”, “using the bathroom” or “putting on makeup”.

By filtering the data set per activity and limiting the results with the duration condition, the amount of respondents who (most likely) showered can be determined. Then, they are grouped into the hour of the day on which they performed the activity and the probability of showering on an average day can be estimated. Figure 3.8 shows the distribution of respondents who complied with the restrictions described above and the probability distribution determined. It is important to mention that due to the small difference between the distribution of weekdays and weekends no distinction was made between them in the final probability distribution.

The probability distribution calculated indicate the percentage of the population who is showering at a given time on an average day. Furthermore, the water consumed is directly related to the duration of the bath, which for the United States has an average duration of 8.2 minutes.\textsuperscript{[33]} To account for the variation of people’s behavior each day, a + - 5% random hourly perturbation was introduced in the creation of the hourly profile for one year.

An example of the calculated average hot water consumption per person for Puerto Rico and the measured consumption of a set of Finnish apartments\textsuperscript{[20]} are shown in Figure 3.9. From the figure it can be seen that although the estimated consumption is higher than the measured for 191 people, it is within the range of the measurements.
Chapter 3. Energy use in Islands

Cooking

Cooking energy consumption is difficult to estimate as it depends not only on the ingredients to be used, but on the cooking methods, cooking times and cooking habits. Cooking methods can be summarized as baking, roasting, broiling, boiling, frying and stewing and can be done either on table top stoves or ovens. [19] In the ATUS, cooking is grouped under the activity “food and drink preparation” which is composed by various activities most related to cooking and some related to drink preparation such as “mixing drinks” and food preparation such as “peeling potatoes”. Being that the activity is comprised mainly of cooking related activities, no filter on activity duration was used. Additionally, the relevance of the activities grouped allow to consider the average duration calculated as a measure of the cooking duration distribution throughout the day. Finally, because there was practically no difference in behavior between weekdays and weekends, the distributions were estimated taking into account the combined data.

Figure 3.10: Cooking distributions.

The resulting cooking probability distribution and cooking duration distribution are shown in Figure 3.10. In the figure, 3 different peaks are distinguished which are characteristic of the 3 meals of the day, with dinner having a higher probability of people cooking. Moreover, the time distribution shows people spend more time cooking in the afternoon than in the morning and evening.
3.2.2 Cooling Energy Demand

Space cooling is usually not considered as an important contributor to the total heat consumption. Nevertheless, it is expected to increase rapidly in the coming century both in high income (usually colder) countries and developing countries (typically warmer). The latter are particularly relevant because the addition of air conditioners to households and service sector buildings could represent a big jump in energy consumption as well as an important contribution to the peak load. Additionally, cooling demands are rarely measured and there is a general lack of information on specific cooling demands as well as on proportions of areas cooled by country and information on the cooling demands for residential and service sector buildings. In the particular case of islands, specifically of tropical islands, air conditioning is or can become an important energy load as temperatures become more extreme and air conditioning more affordable. Moreover, many tropical islands’ main economic activity is tourism for which air conditioning is a very valuable feature. Thus, it is of interest to estimate the cooling requirements of islands and evaluate the possibilities of supplying it with renewable energy and in particular of avoiding excessive electricity consumption which could affect the reliability of the electricity system. For instance, an interesting case could be made for district cooling with seawater air conditioning (SWAC).

Various methods have been proposed in the literature to estimate the cooling demand for residential and service sector based on cooling degree days (CDD) or on the European cooling index (ECI), but none have been used to estimate the hourly cooling demand. Furthermore, it is relevant to estimate and differentiate between the residential sector cooling demand and that of the service sector. The former is larger in size, but the latter is more constant and energy intensive.

In general terms, the thermal cooling demand depends on the climatological conditions, space to be cooled and heat gains caused by appliances and people and it can be estimated by doing an hourly energy balance of the heat needed to be removed from the space cooled in order for it to be at a specified comfort temperature ($T_{\text{comf}}$). The most important climatological conditions are temperature and irradiance and that information is readily available for almost every location. The simplified hourly energy balance of a space to be cooled taking into account only solar gains and the space volume is shown in below. It is important to note that energy efficiency measures such as insulation is not taken into account, however, if information is available it could be included in the energy balance without any problem.

$$P_{\text{cool}}(t) = \frac{(V_{\text{cool}} + V_{\text{vent}}) \cdot \rho_{\text{air}} \cdot c_{\text{p,air}}}{3600} \cdot (T_a(t) - T_{\text{comf}}) + A_{\text{window}} \cdot I(t) \cdot \alpha_{\text{window}}$$  \hspace{1cm} (3.1)

Where:
- $P_{\text{cool}}$: Cooling load in Wh.
- $V_{\text{cool}}$: Built volume to be cooled in m$^3$.
- $V_{\text{vent}}$: Total ventilation required in an hour in m$^3$.
- $\rho_{\text{air}}$: Air density in kg/m$^3$.
- $c_{\text{p,air}}$: Air heat capacity in J/kg·K.
- $T_a$: Ambient temperature in °C.
- $T_{\text{comf}}$: Specified indoor comfort temperature in °C.
- $A_{\text{window}}$: Total window area in m$^2$.
- $I(t)$: Irradiance in W/m$^2$.
- $\alpha_{\text{window}}$: Window transmission coefficient.
To estimate the electricity cooling demand, it is necessary to divide by the air conditioner seasonal energy efficiency ratio (SEER). Werner estimated that the average SEER for Europe is 3.1.[27]

$$P_{cool_{elec}} = \frac{P_{cool}}{SEER}$$  \hspace{1cm} (3.2)

From eq. 3.1, some of the parameters are trivial and available. However, the total volume to be cooled and the total window area are statistics that can prove to be very difficult to find, specially for small tropical islands, but can be indirectly estimated based on more accessible data.

For the residential sector, the average floor area per capita per country has been collected by UN Habitat and Eurostat. For the service sector, data exists for the European Union collected by Eurostat. Furhtermore, M. Isaac and D.P. van Vuuren found that there is a correlation between the wealth of a nation in terms of its GDP per capita ($USD/capita$) and the average housing areas ($m^2/capita$) and can be described by [25]:

$$Floor_{res} = 6.33 \cdot ln(x) − 28.95$$  \hspace{1cm} (3.3)

The fitted equation is a logarithmic function in which at very low income the residential floor area is small but rises at a fast rate with increasing income and then stabilizes growing at a much lower rate when the GDP per capita reaches 10 000 $USD$. In a similar way, the average floor area for the service sector can be estimated from the Eurostat data as shown in Figure 3.11.

The total average built volume is then:

$$V_{built} = Floor \cdot population \cdot height$$  \hspace{1cm} (3.4)

Nevertheless, not all built spaces are cooled. McNeill and Letschert found that the fraction of houses that owned an air conditioner, in other words, the fraction of the total space cooled, depended on two parameters: climate maximum saturation (CMS) and availability [24], as shown by eq.3.5.
3.2. Heat energy demand

\[ \text{Saturation} = \text{Availability}(\text{income}) \cdot CMS(CDD) \]  
(3.5)

The CMS states the maximum fraction of space that is likely to be cooled. The warmer the place, the higher the expected fraction to be cooled. Thus, the CMS can be found by doing a regression on the fraction of cooled space and the CDD. For the residential sector, \([24]\) found using data for the United States that the CMS can be approximated by:

\[ CMS_{res} = 1 - 9.494 \cdot e^{-0.00187 \cdot CDD} \]  
(3.6)

This equation holds under the assumption that “current penetration rates in the USA are the maximum for a climate with a given amount of CDD’s” and can be seen in Figure 3.12a. Similarly for the service sector, a CMS approximation can be found using the Eurostat data. Although useful, it is important to note that it is very limited, particularly in the range of CDD as most of the European countries have a short hot period compared to tropical regions. For that reason, the CMS for the service sector was approximated by two different linear equations as shown in Figure 3.12b. The first one from 0 to 1400 CDD is estimated using the cooled percentage data. The second region is proposed as an estimation for higher CDD taking into consideration that the maximum cooled area in Europe is around 80% in Spain.

The availability is a function which represents the dependence of air conditioner adoption with the income per capita. With higher income it is expected that the amount of installed air conditioners increases. Following the equation proposed by \([24]\), Isaac and van Vuuren found the availability as function of income\([25]\):

\[ Availability = \frac{1}{1 + e^{4.152 + 0.239 \cdot \text{income} / 1000}} \]  
(3.7)

Where income is the GDP per capita in purchasing power parity (PPP) adjusted 1995 US dollars. The total volume to be cooled is then:

\[ V_{cool} = V_{built} \cdot \text{Saturation} \]  
(3.8)

Analogously, the window area can be estimated as a fraction of the total floor area to be cooled.
The wall to floor ratio ($\beta_{\text{wall-floor}}$) of a building depends on the use of the building, but typically for office buildings it is between 0.3 and 0.5 and for residential apartments slightly higher (0.6-0.8). [36] Similarly, the windows requirements vary with the application, for this thesis a window to wall ($\beta_{\text{window-wall}}$) ratio of 0.4 is assumed. Hence, the total amount of windows can be calculated as:

$$A_{\text{window}} = \text{Floor} \cdot \text{Saturation} \cdot \beta_{\text{wall-floor}} \cdot \beta_{\text{window-wall}}$$  (3.9)

The ventilation requirements are dependent on the amount of people occupying the building and the activities carried out inside. For a building where there is not a high concentration of people and normal activities are performed a flow rate of $25 \, m^3/h\cdot\text{person}$ is adequate. The ventilation requirements range from $25 \, m^3/h\cdot\text{person}$ to $50 \, m^3/h\cdot\text{person}$ when more intensive activities are performed such as physical exercise or work with chemical substances (e.g. solvents). [37]

Finally, the condition of when the cooling is required is relevant. In the ECI [38], cooling is considered as needed only when the ambient temperature is above $29^\circ C$. Service sector spaces such as offices and stores are usually kept at the comfort temperature as the comfort of the people impacts directly their earnings. For that reason, the cooling ambient temperature was lowered to $25^\circ C$, which means that cooling is done more often. For the residential sector, it is assumed that at $28^\circ C$ cooling is required, as a high usage has a direct impact on their electricity bill.

With the equations described above, it is possible to estimate the hourly cooling demand for an island. Table 3.2 shows the comparison between the estimated values and those reported in the literature for Cyprus and Rhodes and Figure 3.13 shows the estimated hourly electricity cooling demand for one year for Cyprus.

<table>
<thead>
<tr>
<th>Table 3.2: Comparison of calculated and reported specific cooling demands.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential - Calculated specific cooling demand $[kWh/m^2]$</td>
</tr>
<tr>
<td>Residential - Werner specific cooling demand $[kWh/m^2]$</td>
</tr>
<tr>
<td>Residential - Jakubcionis specific cooling demand $[kWh/m^2]$</td>
</tr>
<tr>
<td>Residential - Jakubcionis equation for specific cooling demand $[kWh/m^2]$</td>
</tr>
<tr>
<td>Service - calculated specific cooling demand $[kWh/m^2]$</td>
</tr>
<tr>
<td>Service - Werner specific cooling demand $[kWh/m^2]$</td>
</tr>
</tbody>
</table>

Note: the literature values for Rhodes are not available, thus the average values for Greece are shown.
Figure 3.13: Yearly electricity demand for cooling in an hourly resolution for Cyprus.
Chapter 4

Island case-studies

Previously, it was stated that islands’ special characteristics made them perfect candidates for high renewable energy integration. This idea has existed for a long time and has gained relevance in the last decades specially in the academic and public sectors, as can be seen from the increase of publications on topics related to renewable energy systems on islands [4] and of aid funded projects on energy related topics in the South Pacific [16]. Although different, island share common characteristics meaning that knowledge and technology transfer could be possible, allowing them to learn from past experiences to accelerate their energy transition. [3] This chapter aims to describe the current island context and present the selected case studies.

4.1 Island context

Islands around the world, although fundamentally diverse, face similar challenges regarding energy security and climate change vulnerability. As in most of the world, electricity is generated mainly through fossil fuels. Islands often possess limited indigenous conventional resources and most of them have small energy systems relying mainly on few fuel oil generators. As a result, together with their isolation from mainland markets, the fuel needs to be imported at high prices and representing in some cases a considerable share of the island’s expenditure (up to 20% of GDP)[39] leaving them exposed to oil price volatility.[2] Additionally, being surrounded by water, they are extremely susceptible to sea level rise jeopardizing in some cases their existence.[40] These challenges and the fact that many islands have substantial renewable energy potential, have motivated them to work toward an energy transition to sustainable energy systems.

Energy transition in islands is a topic that has been ongoing for some time. Already in 1997 on the first European Conference on Sustainable Island Development it was recognized that “non-renewable energy sources must be considered as provisional solutions, unsuitable as a long term solution to the energy problem in islands.”[15] The transition, however, is not an easy task as it encompass various challenges and barriers that need to be overcome such as technical difficulties of high renewable integration islanded systems, lack of information and knowledge of renewable potentials and configuration possibilities, scarcity of financial resources of small island developing states (SIDS), lack of regulatory framework and legislation, to name a few (Blechinger et al. [7] identified 31 main barriers). To support these communities on their energy transition efforts, various initiatives have been pushed forward for specific island groups such as IRENA’s lighthouse and islands initiative, US DoE’s Energy Transition Initiative (through NREL), Carbon
War Room 10 island challenge, DAFNI’s smart islands initiative, among others. Additionally, energy related aid projects [16] and academic research involving sustainable energy on islands have increased in the last decade [4]. Together with these initiatives, various SIDS have established ambitious renewable targets for the upcoming years (2020-2050). [4, 2] Although the carbon emission reduction resulting from these measures is small compared to the total world emissions and despite the fact that some of those targets could be considered not consistent to the countries’ own potential and are dependent on foreign aid funding [2], islands seek to lead by example in demonstrating that high penetration of renewable energy is feasible and gain credibility and leverage for climate change negotiations. [16]

Islands have been considered as “laboratories of the future of energy sustainability” [15] and as such, it is important to understand to which extent the solutions achieved in one particular island could be applied in other islands and regions. Distributed around the world, there are more than 10,000 inhabited islands with a population of approximately 740 million people. Moreover, 91% of that population lives in 29 highly populated islands of over 3.5 million people whose energy demands are similar to those of continental areas. However, the remaining 9% live in smaller islands with isolated island systems as the ones described previously. It is in this range of smaller islands where projects and studies aiming to high renewable penetration energy systems are being performed. The total amount of small islands, as well as the population threshold for feasible 100% renewable systems is a disputed topic in the literature. Dean Gioutso established that the relevant islands for studying these systems were within a population of 10,000 to 1,000,000 people. The lower bound’s reason being that solutions exist for small off-grid systems and have been thoroughly studied. He identified 298 islands within those bounds. [4] Blechinger et al. considered that islands within 1,000 and 100,000 were mainly diesel based minigrids which could transition to sustainable energy systems, identifying 1785 islands. [7] Meschede et al. considered that islands with a population of less than 3.5 million and with a distance to mainland of at least 10 km were candidates for the implementation of high renewable penetration identifying 1,087 islands. Additionally, from the analysis of those islands, they proposed a classification regarding their opportunities to implement renewable energy. In this classification, the islands are grouped in clusters according to their socio-economic and physical characteristics (letters) and their climatic data (roman numerals) as can be seen in Figures 4.1a and 4.1b. In particular, climatic clusters are as follows: I-II are the coldest islands with cluster II having higher winds speeds and lower temperature variance, III-IV are moderate climate islands the difference being the higher seasonal dependence of IV, V are islands located close to the tropics with high irradiance but dry, VI-VIII are tropical islands the difference between them is the seasonality and variance of rainfall and the wind speed. For the socio-economic/physical clusters letters A-D are lower income countries while E-H are higher income countries. Nevertheless, it is important to mention that the study found this groups showed “very weak structures”. Through this classification, the authors aim to show common features of islands to “disseminate and transfer single island concepts to islands with best suited conditions for similar energy systems”. [3]
4.2 Island case studies selection

For thesis a selection of islands is required to be done in order to be able to perform the assessment of the optimal configurations and evaluate the effect of the supply and demand scenarios chosen. The amount of islands to be selected was limited to 10-12 as it was considered that this amount already expands the work developed previously allowing to perform a more global assessment and it is low enough to be done in the duration of the thesis. In order to guarantee as good as possible that the selected islands are representative of a broader amount of islands, the were selected based on the following criteria:

1. The most important climates and water bodies need to be represented.
2. Include islands representing a wide range of population (10,000[4]-3,500,000[3]) and wealth (GDP per capita) and thus, of the electricity system.
3. Availability of the required data.
4. Islands studied previously in [4] and [5] should be included for comparison and validation.
5. Focus on tropical islands. Tropical islands on particular must be well represented to evaluate the heat electrification scenarios.
6. Must not be grid connected and preferably have renewable targets set.

For this thesis, 11 case study islands (Figure 4.2) were selected:

1. Aruba
2. Cyprus
3. Gran Canaria
4. Mauritius
5. Oahu
6. Puerto Rico
7. Rarotonga
8. Rhodes
9. Shetland
10. Streymoy
11. Sumba

The selected islands main characteristics are summarized on Table 4.1. As can be seen, 6 of the selected islands are tropical islands (clusters VI-VIII), 2 are northern islands (cluster II) with big
resource seasonality and low temperatures, 2 are moderate climate islands in the Mediterranean with high seasonality in their solar resource (cluster IV) and 1 is located close to the tropic with good solar resource but a dry climate (cluster V). Additionally, 3 are cataloged as low income islands (A-D) and 8 medium-high income islands (F-H). Finally, of the considered case-studies, 6 islands are part of developed economies while 5 are either part of developing countries or SIDS.

Figure 4.2: Selected case studies.
Table 4.1: Selected case studies island characteristics.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>Caribbean Sea</td>
<td>103,889</td>
<td>180</td>
<td>577.2</td>
<td>189</td>
<td>27,320</td>
<td>18,448</td>
<td>5.2</td>
<td>3,833</td>
<td>VI-B</td>
</tr>
<tr>
<td>Cyprus</td>
<td>Mediterranean Sea</td>
<td>1,165,300</td>
<td>9,250</td>
<td>126.0</td>
<td>374</td>
<td>23,324</td>
<td>23,250</td>
<td>5.1</td>
<td>1,185</td>
<td>IV-H</td>
</tr>
<tr>
<td>Gran Canaria</td>
<td>North Atlantic Ocean</td>
<td>838,397</td>
<td>1,530</td>
<td>548.0</td>
<td>1,949</td>
<td>22,422</td>
<td>18,985</td>
<td>5.7</td>
<td>1,101</td>
<td>V-F</td>
</tr>
<tr>
<td>Mauritius</td>
<td>Indian Ocean and Persian Gulf</td>
<td>1,262,600</td>
<td>2,040</td>
<td>618.9</td>
<td>828</td>
<td>9,627</td>
<td>13,856</td>
<td>5.2</td>
<td>2,111</td>
<td>VI-F</td>
</tr>
<tr>
<td>Oahu</td>
<td>Pacific Ocean and Persian Gulf</td>
<td>953,207</td>
<td>1,545</td>
<td>617.0</td>
<td>1,220</td>
<td>50,130</td>
<td>34,390</td>
<td>5.3</td>
<td>2,608</td>
<td>VIII-F</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>Caribbean Sea</td>
<td>3,474,200</td>
<td>8,870</td>
<td>391.7</td>
<td>1,338</td>
<td>29,920</td>
<td>25,481</td>
<td>5.0</td>
<td>3,375</td>
<td>VI-F</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>Pacific Ocean</td>
<td>10,572</td>
<td>67.6</td>
<td>156.4</td>
<td>652</td>
<td>8,146</td>
<td>9,153</td>
<td>4.6</td>
<td>2,358</td>
<td>VI-C</td>
</tr>
<tr>
<td>Rhodes</td>
<td>Mediterranean Sea</td>
<td>115,490</td>
<td>1,400</td>
<td>82.5</td>
<td>1,216</td>
<td>26,783</td>
<td>18,114</td>
<td>4.6</td>
<td>1,188</td>
<td>IV-H</td>
</tr>
<tr>
<td>Shetland</td>
<td>North Atlantic Ocean</td>
<td>23,310</td>
<td>1,466</td>
<td>15.9</td>
<td>450</td>
<td>41303</td>
<td>28,725</td>
<td>2.2</td>
<td>0</td>
<td>II-G</td>
</tr>
<tr>
<td>Streymoy</td>
<td>North Atlantic Ocean</td>
<td>22,400</td>
<td>373</td>
<td>60.1</td>
<td>789</td>
<td>55,885</td>
<td>27,686</td>
<td>1.9</td>
<td>0</td>
<td>II-H</td>
</tr>
<tr>
<td>Sumba</td>
<td>Malay Archipelago</td>
<td>685,186</td>
<td>11,153</td>
<td>61.4</td>
<td>1,225</td>
<td>658</td>
<td>446</td>
<td>5.3</td>
<td>3,273</td>
<td>VII-C</td>
</tr>
</tbody>
</table>

* Equivalent sun hours (ESH) is the average daily irradiance of a location in kWh/m²·day. [43] These ESH were determined taking into account the optimum tilt angle for each location.

** CDD refers to the cooling degree days calculated as \( \sum_{i=1}^{365} T_{\text{mean}} - 18^\circ C \)
4.3 Electricity Demand Data

The electricity system characteristics (for calculating emissions and fuel prices) as well as an hourly averaged electricity demand curve is used as input for the proposed model. For the hourly electricity demand curve, real data was used whenever available. However, for the cases when partial information was available, the hourly time series had to be created. Whenever a typical day was available, the shape of the curve was used for the whole year. Additionally, whenever data on the monthly mean demand and/or maximum demand was available the data was scaled to meet the reported values. For the specific case of Mauritius, a daily profile was missing so a day of March from Gran Canaria was used and scaled accordingly. The data sources used are shown in Table 4.2 and the main characteristics of the selected islands are summarized in Table 4.1. The hourly averaged demand timeseries are shown in Appendix A.

### Table 4.2: Selected electric system data sources.

<table>
<thead>
<tr>
<th>Island</th>
<th>Year</th>
<th>Data duration</th>
<th>Reference 1</th>
<th>Reference 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>2011</td>
<td>1 day</td>
<td>[5, 44]</td>
<td>[8]</td>
</tr>
<tr>
<td>Cyprus</td>
<td>2015</td>
<td>1 year</td>
<td>[45]</td>
<td>[46]</td>
</tr>
<tr>
<td>Gran Canaria</td>
<td>2015</td>
<td>1 year</td>
<td>[4, 47]</td>
<td></td>
</tr>
<tr>
<td>Mauritius</td>
<td>2014</td>
<td>Monthly mean and max demand</td>
<td>[48]</td>
<td>[49]</td>
</tr>
<tr>
<td>Oahu</td>
<td>2015</td>
<td>1 year</td>
<td>[50]</td>
<td>[51, 52]</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>2016</td>
<td>3 months</td>
<td>[53]</td>
<td>[54, 55]</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>2014</td>
<td>9 months</td>
<td>[4]</td>
<td>[56]</td>
</tr>
<tr>
<td>Rhodes</td>
<td>2010</td>
<td>1 year</td>
<td>[4]</td>
<td>[57]</td>
</tr>
<tr>
<td>Shetland</td>
<td>2015</td>
<td>1 day per month</td>
<td>[5]</td>
<td>[5]</td>
</tr>
<tr>
<td>Streymoy</td>
<td>2015</td>
<td>1 year</td>
<td>[4]</td>
<td>[58]</td>
</tr>
<tr>
<td>Sumba</td>
<td>2013</td>
<td>1 day</td>
<td>[4]</td>
<td>[59]</td>
</tr>
</tbody>
</table>

### Table 4.3: Selected case studies energy system characteristics.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>915.7</td>
<td>8813.9</td>
<td>104.5</td>
<td>129.9</td>
<td>0.25</td>
</tr>
<tr>
<td>Cyprus</td>
<td>4668.4</td>
<td>4006.2</td>
<td>532.9</td>
<td>964.0</td>
<td>0.16</td>
</tr>
<tr>
<td>Gran Canaria</td>
<td>3383.9</td>
<td>4036.1</td>
<td>386.3</td>
<td>547.5</td>
<td>0.13-0.18</td>
</tr>
<tr>
<td>Mauritius</td>
<td>2821.2</td>
<td>2234.4</td>
<td>322.1</td>
<td>459.5</td>
<td>0.25</td>
</tr>
<tr>
<td>Oahu</td>
<td>7086.2</td>
<td>7434.0</td>
<td>808.9</td>
<td>1204.0</td>
<td>0.28</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>20740.2</td>
<td>5969.8</td>
<td>2367.6</td>
<td>3114.0</td>
<td>0.24</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>26.6</td>
<td>2515.2</td>
<td>3.0</td>
<td>4.5</td>
<td>0.44</td>
</tr>
<tr>
<td>Rhodes</td>
<td>851.9</td>
<td>7376.7</td>
<td>97.3</td>
<td>212.8</td>
<td>0.2</td>
</tr>
<tr>
<td>Shetland</td>
<td>226.4</td>
<td>9711.0</td>
<td>25.8</td>
<td>39.5</td>
<td>0.22</td>
</tr>
<tr>
<td>Streymoy</td>
<td>142.4</td>
<td>6356.1</td>
<td>16.3</td>
<td>25.4</td>
<td>0.26</td>
</tr>
<tr>
<td>Sumba</td>
<td>41.2</td>
<td>60.2</td>
<td>4.7</td>
<td>7.3</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Additionally, the current configuration of conventional generating units is shown in Figure 4.3.
The figure shows the composition of generating units regarding the fuel used. It was found that most of the generation was done via diesel and HFO, with the exception of Mauritius where an important share of the generation is done with coal.

![Figure 4.3: Installed capacity of conventional generation per fuel type for selected islands](image)

### 4.4 Meteorological Data

The renewable energy potential of a place is greatly determined by its climatic conditions. Similar to the demand data, hourly averaged meteorological data is needed as input for the proposed model. For this thesis, information on ambient temperature, wind speed, solar irradiance, wave height and period, tidal current speed and ocean’s temperature is needed. It was of interest to keep the number of data sources as low as possible in the attempt to have comparable measurements that allow the comparison between the case studies. Therefore, global data bases were used and are summarized in Table 4.4. The majority of the data could be sourced in global datasets except for tidal current data which was mainly unavailable except for specific places where studies have been made to assess its tidal potential. It is important to mention that by using this global approach, specific on site studies with more accurate and detailed measurements might be available and could prove to be useful for further projects development.

The databases used to source the information were:

<table>
<thead>
<tr>
<th>Meteorological variable</th>
<th>Database</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>Meteonorm 7</td>
</tr>
<tr>
<td>Irradiance</td>
<td>Meteonorm 7</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Meteonorm 7</td>
</tr>
<tr>
<td>Tidal current speed</td>
<td>NOAA and [60]</td>
</tr>
<tr>
<td>Wave height and period</td>
<td>BMT ARGOSS Waveclimate</td>
</tr>
<tr>
<td>Ocean’s temperature</td>
<td>NOAA WOA</td>
</tr>
</tbody>
</table>
- Meteonorm 7: is a global database fed by various data sources including weather stations and geostationary satellites that allows the user to generate typical reference years by averaging 10 years of data. It allows to gather over 30 different weather parameters of any part of the world using real measurements and interpolations. Although Meteonorm states that their data is accurate, it also notes that the output data “only approximates the real situation”. Nevertheless, the precision and availability of information is enough for the objectives of this thesis.

- BMT Argoss’ Waveclimate: is a global database that provides information on wind and wave statistics. The database consists of “calibrated long-term global and regional model hindcasts, together with satellite observations”. The model is calibrated with buoys data and can provide information from 1992. It is important to mention that tropical storms are not represented in the database.

- World Ocean Atlas NOAA: is a global dataset that contains ocean information on “temperature, salinity, dissolved oxygen, Apparent Oxygen Utilization (AOU), percent oxygen saturation, phosphate, silicate, and nitrate at standard depth levels for annual, seasonal, and monthly compositing periods”.

In the following subsections the monthly averaged resources are shown. Information on how the hourly averaged information was created is provided and the hourly timeseries can be seen in Appendix A.

**Temperature**

Temperature data was obtained from Meteonorm. When generating the typical reference year, the software has the option to provide hourly data. The monthly averaged temperature is shown in Figure 4.4. The seasonal variation typical of Northern and Mediterranean islands and the stable higher temperatures of tropical islands are clearly seen in the figure.

![Figure 4.4: Monthly averaged temperatures for selected islands.](image)

**Wind**

Wind speed data was readily available on the different data sources used. Nevertheless, because it was onshore wind that was of interest, Meteonorm was used. The Northern islands have
higher and Gran Canaria and Aruba possess the most wind resource as can be seen from Figure 4.5.

Irradiation

Solar irradiation data was sourced from Meteonorm. Irradiation data generation is the main feature of Meteonorm, allowing to add various corrections for the typical reference year generation. In particular, it allows the user to set fixed azimuth (surface orientation) and tilt (surface inclination). This is relevant because for PV electricity generation the total irradiation available to the panels greatly influences their performance and costs. Breyer et al. have found that an optimized tilt angle can increase the annual irradiation up to 35%. [61] For that reason, the optimum tilt angles for the selected islands were calculated. Figure 4.6 shows the monthly averaged solar resource considering the optimum orientation for each selected island.

Optimum Tilt Angle

The optimum orientation of a PV module depends on the location where the module is going to be installed. To calculate them, a matlab routine based on the procedure proposed by [43]
was used. The procedure calculates the position of the sun throughout the year and corrects the total direct and diffuse light reaching the surface of the panel. The tilt angle was evaluated every 10° while the azimuth every 20°. Figure 4.7 shows the effect of the orientation of the PV panels for 4 selected locations. The yellow values represent the maximum annual irradiation while the blue the lowest. For regions near the tropics as Rarotonga or Puerto Rico it can be seen that low tilt angles are optimum as the sun is high on the sky most of the year. In comparison, northern places as Shetland need to be oriented to the south and have higher tilt angles as the sun is low during winter. The calculated optimum tilt and azimuth angles are shown in Table 4.5. It is important to mention that for large PV installations the tilt angles might not be the energy optimum but the cost optimum. This is due to the fact that the cost of PV installations depend largely on the area needed and the amount of balance of systems required. [61] Nevertheless, for this thesis the energy optimums were used.

Figure 4.7: Effect of PV orientation in electricity generation.
4.4. Meteorological Data

Table 4.5: Optimum PV orientation for selected islands

<table>
<thead>
<tr>
<th>Island</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Tilt</th>
<th>Azimuth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>12.512</td>
<td>-69.972</td>
<td>10</td>
<td>SSE</td>
</tr>
<tr>
<td>Cyprus</td>
<td>35.126</td>
<td>33.430</td>
<td>30</td>
<td>S</td>
</tr>
<tr>
<td>Gran Canaria</td>
<td>27.920</td>
<td>-15.547</td>
<td>25</td>
<td>SSW</td>
</tr>
<tr>
<td>Mauritius</td>
<td>-20.348</td>
<td>57.552</td>
<td>15</td>
<td>N</td>
</tr>
<tr>
<td>Oahu</td>
<td>21.439</td>
<td>-158.000</td>
<td>20</td>
<td>SSW</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>18.221</td>
<td>-66.590</td>
<td>15</td>
<td>SSE</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>-21.229</td>
<td>-159.776</td>
<td>20</td>
<td>NNW</td>
</tr>
<tr>
<td>Rhodes</td>
<td>36.434</td>
<td>28.218</td>
<td>30</td>
<td>S</td>
</tr>
<tr>
<td>Shetland</td>
<td>60.530</td>
<td>-1.266</td>
<td>55</td>
<td>S</td>
</tr>
<tr>
<td>Streymoy</td>
<td>61.893</td>
<td>-6.912</td>
<td>55</td>
<td>S</td>
</tr>
<tr>
<td>Sumba</td>
<td>-9.699</td>
<td>119.974</td>
<td>10</td>
<td>NEE</td>
</tr>
</tbody>
</table>

Wave

Wave data was sourced from Waveclimate. The database allows to generate timeseries with the information of the selected place from 1992 to 2016 in time steps of 3 hours. For this thesis 2015 was selected as reference year for all islands. Additionally, the hourly timeseries was created by interpolating the 3 hour data provided. Figure 4.8 shows the monthly averaged values for each of the selected islands. It can be seen that the higher waves as well as energy periods occur in northern islands meaning they have the higher wave energy potential.

![Wave data](image)

Figure 4.8: Monthly averaged wave data for selected islands.

Tidal Current Speed

It was not possible to find a global dataset containing tidal current speeds. Information on tide ranges is more readily available, nevertheless tidal range technology is more intrusive and capital intensive and was not considered in the model. It was found, however, site specific information measured by buoys for three islands: Oahu, Puerto Rico and Shetland. The data for Oahu and Puerto Rico was obtained from NOAA for a whole year while the information for Shetland was obtained for 15 days [60] and extended to generate one year.[5]. The monthly averaged tidal current speeds are shown in Figure 4.9.
Ocean Temperature Gradient

Ocean temperature at the surface and 1000 m was required as an input for the model to assess the OTEC potential. This information was retrieved from the World Ocean Atlas of NOAA which provides monthly averages at different depths. From there, the hourly timeseries were created. If a month’s average was missing, it was replaced by the year average at the location. Additionally if the information was not available at the required depths it was assumed that OTEC was not feasible at that location. Figure 4.4 shows the ocean’s surface temperature for the selected islands.
Chapter 5

Modeling

To determine the optimal configurations of hybrid renewable energy system (HRES), a model simulating the electric system of the islands was developed on Matlab based primarily on the work done previously by Leonore van Velzen and Dean Gioutsos [5, 4].

Although various computer tools are available to design and evaluate HRES such as iHOGA, HYSIM, AREs, SOMES and HOMER, one of the goals of the model is to be customizable and expandable for further work. [8] Additionally, it is of interest to investigate the roles of ocean technologies on HRES in islands, and as stated by [5], available softwares do not include this technologies in their analysis. Furthermore, the model needs to be general enough to be suitable for different islands but reliable enough to produce quality results.

This chapter is structured as follows. First, a brief theoretical background of relevant concepts and characteristics of energy systems and of generating technologies will be provided. Then the model will be described as a whole and the general assumptions will be stated followed by a specific description of each one of the components of the model. Finally, a description of the control strategy and residential heat demand electrification blocks will be given.

5.1 Background

Island Electricity Systems

In general, an electricity system is a combination of different engineering systems which involve huge investment in infrastructure and that operates in a decades time horizon and have the objective of generating, transporting and supplying electricity to the consumers. The specific characteristics of any electricity system is determined by factors such as: socio-economic context, resource availability, spatial constraints (access to other electricity systems), electricity consumption patterns, etc. For that reason, every single electricity system in the world is unique. However, there are major differences between a mainland system and an island / insular system as summarized on Table 5.1. [40]

Historically, mainland electricity systems were the first ones to develop and have continued to do so for the past century. Consequently, the network and technology design of the system
Table 5.1: Characteristics of Mainland and Island electricity systems [40, 62]

<table>
<thead>
<tr>
<th>Mainland</th>
<th>Island</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interconnected with neighboring of cities, states and countries in the economic and electric system level.</td>
<td>Isolated from other systems and economies.</td>
</tr>
<tr>
<td>Very large amount of consumers that smooth small changes in electricity demand by few customers.</td>
<td>Fewer customers which can cause more drastic and unpredictable changes in power consumption.</td>
</tr>
<tr>
<td>Availability of many plants of different sizes allowing them to operate at their optimum.</td>
<td>Restriction on the size of the generators and on the access to multiple fuels. Mainly diesel/HFO internal combustion engines (ICE).</td>
</tr>
<tr>
<td>Diversity of generation which allow to have unit specialization.</td>
<td>ICE power plants are used for baseload generation, frequency control and load-following tasks.</td>
</tr>
<tr>
<td>At low integration of renewable technologies, installed controllable generators can cope with the variability of the renewable technologies.</td>
<td>ICE power plants can cope with the variability of renewable technologies but at an even more expensive price due to the additional cycling of the plant.</td>
</tr>
<tr>
<td>Affordable electricity prices.</td>
<td>Expensive electricity prices.</td>
</tr>
</tbody>
</table>

was done to satisfy their particular needs, and were adopted later by islands whose needs differed greatly. For that reason, it is important to characterize and understand the differences and particularities of island systems in order to model and design a system that satisfy its needs.

Moreover, due to the fact that generation is often done by a small amount of fossil fueled generators, the reliability of the system is typically low (specially for small systems) as outages and fuel shortages can be expected. Thus, it is very important to understand the notions of power system stability and reserve adequacy. Power system stability refers to the ability of a power system which is in normal operation to regain a state of operating equilibrium after it has been exposed to a physical disturbance or contingency. There are 3 types of stabilities: rotor angle, voltage and frequency, being the last one the most important. When the grid is operating at off-nominal frequency (typically 50 or 60 Hz), negative and hazardous situations might occur such as resonances in rotating machines that tear them because of mechanical vibrations, changes in the speed of asynchronous machines, overheating of transformers and machines because of increased core loses, flickering, etc. [62]

Reserve adequacy of an electricity system refers the availability of enough dispatchable generating technologies to assure a stable and reliable electricity supply. In power systems, reserves
are typically of two types: event and non-event reserves. Event reserves are responsible for coping with sudden, infrequent imbalances while non-event reserves are responsible for continuous imbalances that occur during normal operation. [6].

**Frequency control.** When an imbalance occurs, frequency has to be restored at its nominal value. This is typically done by a 3 level control strategy. Primary frequency control is used to stabilize the grid and avoid further deviations and is done by generators with a speed governor. However, primary control cannot restore the frequency back to its nominal value. Thus, secondary control is used. Secondary control is conformed by spinning and non-spinning reserves. The former are generators that are already running at the grid frequency and the latter are idle fast start engines. [6, 62]. As defined by [63] "the spinning reserve is the unused capacity which can be activated on decision of the system operator and which is provided by devices which are synchronized to the network and able to affect the active power."

**Hybrid Renewable Energy Systems**

The integration of renewable energy technologies in the electricity grid has been investigated for the last half century, however, the intrinsic variability of many of the renewable energies limit their integration to the electricity systems. To overcome these limits as well as to enhance the system’s reliability, the hybrid renewable energy system (HRES) concept was introduced. A HRES is conformed by 2 or more generating sources which ideally complement each other increasing the reliability of the system.[8] For instance, it has been shown that the combination of PV, wind, storage and conventional generation can provide a reliable and and economic supply of electricity in off-grid applications [12, 9, 7]. An optimal HRES should be cost-effective and have a performance such that all of the load requirements are met. Figure 5.1 shows the general architecture of a HRES.

Figure 5.1: Hybrid Renewable Energy System general architecture.[8]
Technologies for energy generation and storage

In the following section the most important technologies for electricity generation will be described and its most important characteristics detailed. A special focus will be put on renewable technologies, particularly on non fully mature technologies such as ocean technologies.

Solar Photovoltaic (PV) technology

Solar photovoltaic technology (PV) get its name from the photovoltaic effect, principle by which it generates electricity from sunlight. PV cells are conformed by (at least) 2 semiconductor materials, one rich in electrons called N-type semiconductor and one deficient called P-type semiconductor. There are various types of PV technologies which depend on the semiconductor material used (c-Si, CIGS, CdTe) and type of the panels, but all work under the same principle. Figure 5.2 shows the configuration of a generic c-Si PV cell.

Sunlight is electromagnetic radiation emitted by the sun. The energy contained in it depends on the wavelength and is quantized in photons. When a high energy photon collides with the semiconductor material of the PV cell, the energy contained in it is transferred to an electron which, by gaining that energy, reaches an excited state in which it can move through the material. If the electron is freed at the junction of the n and p semiconductors, there is a probability that the electron will go from one semiconductor to the other. If enough electrons move, the local imbalance of charges will generate a potential difference at the junction, and this potential difference generated as a response to the electromagnetic radiation is called the photovoltaic effect. The excited (generated) electrons naturally lose the extra energy gained (as heat) and return to their normal state, this is called recombination. When those sunlight-generated electrons are removed from the material before they recombine, electricity is generated. The efficiency of a solar panel depends on different factors such as the semiconductors selected, the width of the layers of the solar cells, the ambient temperature, the orientation of the panel with respect to the sun, among others. Figure 5.3 shows the difference in performance of a PV module under different temperature conditions.
5.1. Background

Of all the PV technologies crystalline silicon (c-Si) is the most widely used and also the most mature. In order to make use of the generated electricity and supply it to the grid, PV panels are coupled with other electronic devices such as MPPT trackers, inverters and charge controllers (called balance of systems (BoS)) forming a PV system. The overall efficiency of a PV system is then the combination of the PV panel efficiency and that of the BoS.

Wind Turbines

Wind turbine technology converts the kinetic energy of the wind to mechanical energy and then to electricity. There are fundamentally 4 types of machine configurations: drag-type, lift-type, Magnus effect and vortex machines. However, most of the commercial wind turbines are lift-type horizontal-axis 3-bladed turbines. Just as PV, wind turbines are a very mature technology with a great variety of turbines of different power ratings (1-8 MW) commercially available.

The kinetic power density carried by the wind is

\[ P_k = \frac{1}{2} \cdot \rho \cdot u^3 \]  

where \( \rho \) is the air density and \( u \) is wind speed. However, the maximum power a wind turbine can generate \( (P_{ideal}) \) is just a fraction \((16/27)\) of the total kinetic power available known as the Betz limit shown in equation 5.2.

\[ P_{ideal} = \frac{16}{27} \cdot P_{kwind} \cdot Area_{rotor} \]  

In reality, only a fraction of the Betz limit can be extracted from the wind. The ratio between the actual electricity generated by the turbine and the maximum power that can be generated is called the power coefficient \( c_p \). The power coefficient accounts for all the other losses occurring on the turbine such as aerodynamic losses, mechanical losses and electrical losses. The real power generated by a wind turbine is then[64]:

\[ P_{real} = \frac{1}{2} \cdot \rho_{air} \cdot u^3 \cdot c_p \cdot Area_{rotor} \]  

![Figure 5.3: Effect of temperature in a PV current-voltage curve. [43]](image-url)
Each commercial wind turbine has its own design and technology and thus, different losses leading to different \( r_p \) values. They are characterized by a power curve which is a representation of the performance of a turbine under different wind conditions. A power curve for a GE 3.6 MW turbine is shown in Figure 5.4

![Figure 5.4: GE 3.6 MW wind turbine power curve.][64]

**Ocean technologies**

Oceans cover 71% of the Earth’s surface, and possess valuable sources of energy which are in the forms of wave, tide, marine current, salinity gradient and ocean thermal gradient.[65] with an estimated total potential of 1.8-33 EJ/year [66] and can be particularly relevant for islands. Although the extreme conditions at the sea makes challenging the development of reliable, durable technologies, in the last decade the development of ocean technologies have continued, with demonstration projects occurring recently and being Europe the most important developer of ocean technologies. Currently, there are 530 MW of ocean energy installed, being tidal the most important.[67, 68]

**Tidal Current**

Tides are a cyclic phenomenon caused by the gravitational attraction of the moon and sun and by the Earth’s own rotation (centrifugal and inertial forces) which causes the sea water level to rise and fall once or twice a day (24h 50min which is the moon’s apparent rotation period around the earth), making tidal based energy an interesting technology as it is highly predictable and climate change is not expected to have any influence on its periodicity.[69] Tidal energy is divided in two main technologies, tidal range and tidal current (or stream). The main difference between both forms of energy extraction is that tidal range uses the potential difference of the high and low water while tidal current aims to use the kinetic energy of the water displaced by the ups and downs of the sea level.

Historically, tidal range has been the dominant technology developed, being the 240 MW La Rance tidal barrage (1967, France) and the 254 MW Shiwa Lake tidal barrage (2011, South Korea) the most important projects. Nevertheless, tidal current is considered attractive because it possesses characteristics considered advantageous such as: low environmental impact, scale and
5.1. Background

modularity, technical similarities to conventional hydroelectricity and wind energy and lower costs compared to those needed for tidal barrages.\cite{70} Thus, the focus of this section will be on tidal current.

The tidal stream resource is estimated to have a en equivalent power similar to wave energy of 2-3\(TW\) out of which 3\% is considered to be accessible for electricity generation.\cite{70} The distribution of the resources, however, is unevenly distributed throughout the world and not necessarily overlaps with tidal range potential, as the speeds and turbulence of the tidal streams depend not only on the time but on the local geography (coastal features, seabed shape and to a lesser extent on local weather conditions\cite{69, 70}). Figure 5.5 shows coastal regions with good tidal resources.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{figure5.5.jpg}
\caption{Location of tidal current resources \cite{70}}
\end{figure}

Tidal current although predictable is highly intermittent. Additionally, it has the added characteristic that when the tide rises (flow phase) the water flows to one direction and when the tide falls (ebb phase) it flows to the opposite with a period in between when no current is present called slack water. As a result, the tidal streams are intrinsically bidirectional which adds to the harsh ocean conditions making the energy conversion technology design even more challenging.

The kinetic power density carried by the tidal stream can be calculated the same way as for the wind by eq. 5.1. As the sea water density is around 800 times bigger than that of the air, a tidal current at low speed carry a significant amount of energy. For instance, a tidal current of 2\(m/s\) has the same power density as a wind of 18.5\(m/s\).

Three main categories of tidal current energy conversion devices can be found: axial flow turbines, cross flow turbines and reciprocating devices, with the horizontal axis turbines being the most widespread \cite{71}. Examples of these converters can be found in Figure 5.6.

Horizontal axis tidal turbines have the same working principle as horizontal axis wind turbines and thus, the power that can be extracted is also limited by the Betz limit and the power generated by the turbine can be calculated with an equivalent equation (eq. 5.4).

\[ P_{\text{tidal}} = \frac{1}{2} \cdot \rho_{\text{water}} \cdot A_{\text{rotor}} \cdot c_p \cdot U^3 \] (5.4)

Additionally, commercial tidal turbines are also characterized by power curves which show their overall performance under different current speeds. Despite all the similarities between wind
Chapter 5. Modeling

and tidal current technologies, the extreme conditions present at the ocean represent the main
difference, and it is in the materials requirements and turbine siting where it becomes more
pronounced because of strong drag forces and torques, seabed rocks limited load bearing capa-
bilities, corrosive environment, fouling, difficulty for maintenance among other causes. [70]

Wave Energy Converters

Wave Energy Converters (WECs), is the name of the technology designed to harness the energy
contained in ocean waves, are of particular interest because wave energy possess characteris-
tics that are considered advantageous among renewable energy sources: high utilization factor
(around 90% compared to 30% of wind and solar), high power density, low environmental im-
pact and good predictability. [72] The global wave resource is estimated to have an equivalent
power of 2TW [70]. Waves are generated by wind, and as a consequence has its biggest poten-
tial on open surfaces particularly between northern 40° - 60° latitudes [73].

Ocean waves, as any other waves are characterized by its amplitude (height), wavelength, period
and frequency. However, ocean waves are far from being linear waves. The height, period and
frequency of surface waves are related to wind velocity and direction. For instance, small waves
could be the product of a local breeze and will go in the same direction while those generated
by storm conditions will be higher, with long periods and multiple directions. Figure 5.7 shows a
typical wave measurement in the rough sea of Scotland.
5.1. Background

For that reason, to model the wave behavior at a specific location measurements and statistical treatment of the data is needed. Usually, a fast Fourier transform (FFT) is used to determine the frequency spectrum \((S(f))\) of the waves and with that determine which waves carry the majority of the energy. The most common parameters used to characterize ocean waves are:

- **Significant Wave Height \((H_s)\)** is defined as the average height of the highest third of waves.

- **Peak Power Period \((T_p)\)** is the reciprocal of the frequency at which the peak of \(S(f)\) is located. It is representative of the higher, more energetic waves.

- **Zero up-crossing Period \((T_z)\)** is estimated from successive upward crossings of the mean water level. Is equivalent to the mean wave period and is representative of the full range of periods in a random sea.

- **Energy Period \((T_e)\)** is the period that a linear wave carrying the same energy as the total random sea would have. \([70]\). The energy period can be determined as the quotient of the two spectral moments \(m_{-1}\) and \(m_0\) when the spectra is known. Nevertheless, typically when reconstructing the overall spectra \(T_e\) is rarely specified but can be estimated as a function of \(T_p\) (eq. 5.5) \([74]\).

\[
T_e = \alpha \cdot T_p
\]

(5.5)

Where \(\alpha\) is a coefficient that depends on the shape of the wave spectrum and is typically between 0.86 and 1. Alternatively, it can be estimated based on \(T_z\) as was done in the Atlas of UK marine renewable energy:

\[
T_e = C_{TR} \cdot T_z
\]

(5.6)

Where \(C_{TR}\) is a constant varying between 1 and 1.17. For the Atlas of UK marine renewable energy a JONSWAP spectrum is assumed with a \(C_{TR}\) of 1.14. \([75]\) (For eq. 5.5 \(\alpha\) would be 0.9 for the same spectrum assumption).

The potential of wave energy usually in \([\text{KW/m}]\) can be determined using the aforementioned parameters as described in \([72]\):
\[ P = \frac{\rho \cdot g^2}{64\pi} \cdot T_e \cdot H_s^2 \] (5.7)

Where \( \rho \) is the water density and \( g \) the gravity constant.

Due to the random nature of waves described before, different approaches of wave energy conversion have been developed and described in literature \([70, 76]\). The most important are described below:

- **Attenuator** is a floating device aligned parallel to the direction of the waves. It is usually thin and long (longer than water wavelengths) and has different sections (articulations). When the wave passes along, it bends and twists extracting the energy and causing a progressive reduction in wave height (called attenuation). The 750 kW Pelamis WEC is an example of this type of WEC. \([73]\) \([70]\)

- **Point Absorber** is the most common type of WEC and also the most advanced one along with OWC \([67]\). It is a floating structure with dimensions smaller than the wavelength. It is able to collect energy from all directions. An example of this device is the Aqua Buoy (150 kW). \([73]\)

- **Oscillating water column (OWC)** as written by \([70]\) consists of a hollow tube or structure, open to the sea below the water line and enclosing a column of water topped by a column of air. Oncoming waves cause vertical oscillations of the water column, which in turn compress and decompress the air, driving a turbine.

- **Overtopping device** is a device store water from waves in a reservoir situated above sea level. The water flows through a hydraulic turbine generating electricity. \([70]\) The 10MW wave Dragon and the SSG WEC are examples of this structures. \([73]\)

The power generated by a WEC, is generally represented in the form of a *power matrix* as shown in **Figure 5.8**.

\[ \begin{array}{c|cccccccccccc}
\hline
T_e (s) & H_s (m) & 5 & 6 & 7 & 8 & 9 & 10 & 11 & 12 & 13 \\
\hline
0.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
1.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
2.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
3.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
4.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
5.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
6 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
7 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
7.5 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
8 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\hline
\end{array} \]

**Figure 5.8.** Pelamis power matrix. \([77]\)
Ocean Thermal Energy Conversion

Ocean Thermal Energy Conversion (OTEC) is a technology that aims to utilize the ocean’s temperature difference between surface seawater and deep (800-1000 m) seawater. In tropical oceans between 30° North and 30° South temperature differences of 20°C can be commonly found, making this region suitable for OTEC. Coincidentally, this tropical band is also where many of the (developing) islands are located making this technology an interesting option for their energy supply. In these tropical regions, the temperature gradient has very small variations through the year, meaning that the electricity output is relatively constant and more importantly, that the capacity factors are high.

Oceans are the most important storage of the sun’s energy. Based on the amount of sun absorbed by the ocean, some (very optimistic) OTEC potentials have been stated of 330-600 TW. In reality, the OTEC potential is way lower, as geographical location plays an important role on the areas where the resource can be exploited and the rate at which cold water is generated at the poles (thermohaline circulation) is limited. Taking the latter into account, Custeau and Jacquier estimated that the potential was of 10 TW. Furthermore, Rajagopalan and Nihous predicted that a 7 TW production would have little influence on the ocean’s temperature fields. In summary, the OTEC potential is in large, in the terawatt scale.

OTEC technology is based on the Rankine cycle (Fig. 5.9) to generate electricity. In it, warm surface seawater is used to generate vapor (1) which will be expanded on a turbine to generate electricity (2). Then, the low pressure vapor will be condensed by rejecting heat to the cold deep seawater (3), and finally being pumped to the initial high pressure (4).

However, due to the low temperatures involved in the cycle, the thermodynamic efficiencies are low with values of 3% being typical. Moreover, depending if the substance used in the cycle is a refrigerant (typically ammonia) or seawater two main types of OTEC plants can be distinguished: closed cycle and open cycle. The main difference between them is that in the closed cycle seawater is used exclusively as heat source/sink and it is the refrigerant which completes the cycle. While in the open cycle process, the surface seawater is flashed at the beginning, generating water vapor and liquid. The water vapor is then used in a low pressure turbine and condensed by means of the deep seawater. It is important to note that in this process the condensate is fresh water which can be used later for other applications.

![Figure 5.9: Closed Rankine cycle diagram.](image-url)
In [80], Gerard Nihous proposed an equation to estimate the power of a closed cycle OTEC plant. To develop the equation, a simplified mass and energy balance of the process showed in Fig 5.10 is performed. In it, the following considerations are made:

- The pumping power required by the working fluid is negligible compared to that generated by the turbine.
- The heat exchange is not ideal, thus the ideal Carnot efficiency is not applicable. An endoreversible cycle in which heat is exchanged irreversibly but at constant temperature is considered, and as a consequence the efficiency can be determined by $\eta_E = 1 - \sqrt{T_2/T_1}$. In OTEC where the hot and cold temperatures are similar $T_1 \approx T_2$, then $\eta_E \approx 1/2 - T_2/2T_1$, meaning that only a temperature drop of half the available temperature difference is allowed at the turbine.
- The working fluid’s turbine and pump are not ideal, thus an efficiency $\eta_T$ is considered.
- A pinch temperature approach is used in the evaporator and condenser with a value of $\Delta T/16$.
- The pumping power needed to maintain the required flow rates of surface and seawater represents approximately a 30% of the electricity generated by the OTEC plant (at design conditions).

As with any heat engine, the power delivered by it can be calculated as the heat input times the efficiency. In the described process, the heat input is the heat load of the evaporator, and the efficiency is the product of the thermodynamic efficiency ($\eta_E$) and the turbine efficiency ($\eta_T$). If we define $\psi$ as the ratio between the surface ($Q_{ww}$) and deep seawater ($Q_{cw}$) flowrates, from the energy balance the temperature difference in the evaporator can be written as:

$$\Delta T_{\text{evap}} = \frac{3 \cdot \psi \cdot \Delta T}{8 \cdot (1 + \psi)}$$

And then, the gross power is:

$$P_G = (Q_{ww} \cdot \rho \cdot c_p \cdot \Delta T_{\text{evap}} \cdot \eta_E \cdot \eta_T)$$

(5.8)

Figure 5.10: Simplified closed cycle OTEC plant. (Based on [78])
And the net power is:

$$P_N = \frac{Q_{ww} \cdot \rho \cdot c_p \cdot 3 \cdot \psi \cdot \eta_T}{16 \cdot (1 + \psi)} \left( \Delta T^2 - 0.3 \cdot \Delta T_{\text{design}}^2 \right)$$  (5.10)

Finally, it is important to note the multifunctional possibilities of OTEC plants. Apart from electricity generation, OTEC plants could support in the generation of fresh water, cooling by means of deep seawater and provide nutrient rich water for aquaculture. [79]. These positive side products can make OTEC relevant specially for islands by allowing them to improve not only in terms of electricity supply but also on food security and cooling costs.[17]

**Battery storage**

Batteries are one of the most used technologies for energy storage with a wide range of applications. In it, electrical energy is stored as chemical energy by a reduction-oxidation reaction. Batteries are conformed by cells formed by an ion conducting electrolyte and two half cells where the reduction-oxidation reaction takes place. Depending on the materials used, the cell chemistry varies, and with it the properties and capabilities of the battery. Batteries are typically classified in two categories: primary and secondary batteries. The former are one-time use non rechargeable devices and the latter are devices designed to be recharged various times. [82] It is this last type of batteries which are of interest for HRES applications. As described before, batteries can provide various services to an electricity system and allow higher integration of renewable energy. The following characteristics are relevant for grid applications:

- Low cost
- Long cycle and calendar life
- High system reliability
- Low maintenance
- Low self discharge rates
- High system efficiency

Currently, there are various cell chemistries commercially available each with its own advantages and disadvantages which have been thoroughly compared in [82]. Sodium-sulphur batteries have been thoroughly used for grid applications, but recently there has been a tendency to shift towards lithium-ion and advanced lead acid. [83], Therefore, these last two chemistries are the ones chosen for this thesis.

**Battery concepts and characteristics**

**Capacity**: Is the amount of charge a battery can store typically in ampere hours (Ah) and is determined by the amount of electrode material contained in the battery. The energy stored in the
battery however, is measured in Wh and is determined by the charge (quantity) and the voltage (chemistry) delivered by the battery. [43]

**State of Charge (SoC) and Depth of Discharge (DoD):** State of charge is defined as the fraction of the battery capacity available for discharge. Analogously, the depth of discharge is the fraction of the battery capacity that has been discharged. Both parameters are complementary and as a consequence their sum always equals 1.

**C-Rate:** Is a measure of the rate at which a battery is discharged relative to the battery’s capacity. It is defined as the maximum capacity that can be retrieved from the battery in 1 hour relative to the battery’s nominal capacity. For a battery with a capacity of 2 Ah a C-rate of 1C means that the battery can be discharged at 2 A for one hour. Furthermore, a C-rate of 2C corresponds of a discharge rate of 4 A in a period of half an hour while a c-rate of 0.5C means that the discharge rate is 1 A and can last for 2 hours. Thus, a c-rate of n means that a battery will be fully discharged in \( \frac{1}{n} \) hours.

**Cycle lifetime:** is the number of charging and discharging cycles that a battery can handle before its capacity drops below 80% of its nominal capacity. The cycle lifetime is affected by the type of battery but also by the DoD at which the battery is cycled and the temperature at which it operates. Figure 5.11 exemplifies the effects of these parameters in the lifetime of a lead-acid battery

![Figure 5.11: Qualitative plot of the cycle lifetime of a lead-acid battery](image)

**Battery efficiency:** is a measure of the availability of energy to be discharged compared to the energy input. Usually, the roundtrip efficiency is used. This is defined as the ratio of the total storage output over the total storage input. In reality it is a combination of two type of efficiencies: coulombic and voltaic. The former refers to the charge available for discharge compared with the charge input. It is usually high (95%) and the losses are primarily due to secondary reactions that occur. The latter is caused by the voltage drop while discharging (as shown in Figure 5.12), and is defined as the ratio of the voltage delivered by the battery while discharging over the voltage at which the battery is charged. [84, 43]
5.1. Background

Charging and discharging regimes: refer to the voltage and current conditions upon which a specific battery is charged and how deep it should be discharged. These regimes are dependent on restraints and conditions of the battery’s chemistry. In the following paragraphs, the charge regimes for lead-acid and Li-ion batteries will be detailed.

Lead Acid The lead acid battery charges using a constant current constant voltage method (CC/CV) and should be charged in 3 different stages. On the first stage a constant current is applied charging the majority of the battery. This step usually takes between 5-8 hours and charges the battery to a SoC of 70%. Then, there is a second charge stage (topping charge) at lower current which will get the battery to a SoC of 100% in 7-10 hours. Finally, there is a third stage called the float charge stage is used to compensate for the self discharge of the battery. The characteristics of these stages are shown in Figure 5.13. Discharge wise, lead acid batteries should not be fully discharged as high DoD cycles greatly decrease the battery lifetime.

Li-ion Lithium ion batteries are also charged with the CC/CV method, however, the charging is much faster. A lithium battery typically takes around 3 hours to be fully charged. As can be seen from Figure 5.14a there are 3 different stages. First the constant current stage that charges up to a SoC of 70% as can be seen from Figure 5.14b. Then the variable current topping stage that charges the battery to 98% and finally the float charge. It is important to note that Li-ion batteries cannot be overcharged, thus the battery needs to be disconnected once it is fully charged. Additionally, Li-ion batteries can be partially charged not compromising its internal
In terms of discharge, Li-ion batteries can be fully discharged. However, typically DoD below 100% are used to increase the battery’s cycle life.

(a) Li-ion battery charging stages. [87]  
(b) Li-ion charging behavior. [87]

Figure 5.14: Li-ion charging characteristics.
5.2 Model Description

The model simulates the performance of a HRES of an island for a timespan of one year in hourly time steps. The performance of the system is done by determining the power generated by the selected renewable technologies, simulating the effect of electrifying domestic hot water and cooking in the residential sector and space cooling in the commercial sector, and by means of a control strategy based on the battery state of charge (SOC), the energy supplied by the battery and by the despatchable generators needed to cope with the demand as well as the available spinning reserves needed to guarantee stability of the system, is determined. Figure 5.15 provides a general overview of how the model is structured.

![Diagram of Model Structure](image)

Figure 5.15: Model structure

5.3 General Assumptions

In order for this model to simulate an island electricity system, certain general assumptions and particular (explained later) were made to simplify the complexity of real island electricity systems. To state the assumptions used is crucial to understand the potential but also the shortcomings of the model.
1. **Initial situation**: As fossil fuel based generation has been the main source of electricity, it is assumed that islands already have in place fuel based generators with the capacity to supply the demand and provide stability services. However, other technologies that could be in place in specific islands such as hydropower, geothermal, PV and wind turbines are not considered in the system. This assumption was made because: 1) the objective of this thesis is to assess the potential of renewable energy and find optimal configurations for a given island, independent of the current deployment/preference of renewable technologies and 2) in reality islands are going to have to undertake a transition from fuel based generation to a HRES. The consequence of this assumption is that as fuel based generators are already in place, the demand will always be met, independent of the renewable energy generation.

2. **Feasibility of the configuration**: As the model will be used to find the optimal configurations given certain objective functions, there is no mechanism that assures that the configuration evaluated is feasible. For instance, the model does not provide any information on the physical constraints related to the topography of the islands, nor on the cost or social acceptability of the deployment of a specific technology. Additionally, it does not evaluate nor takes into account the possible changes that could be needed in the grid to support the evaluated configuration. Nevertheless it is important to note that this model is used coupled with an optimization routine, and in the optimization by means of the selected objective functions and constraints, some of those limits for implementation can be taken into account.

3. **Deterministic single year model**: The model evaluates the performance of the HRES for a timespan of 1 year in hourly time steps. Additionally, it is deterministic as the meteorological data profiles and the demand data of the whole year is known since the beginning of the simulation. These assumptions are relevant because: 1) When the model is used for sequential analysis such as determining the levelized cost of electricity (LCOE) for the years of the project lifetime, the demand and power generated will remain constant for that period, neglecting the effect of time. 2) The deterministic approach removes all the randomness present in real life systems. With this approach, no forecasts are needed neither in the short term for demand predictions or in the long term for demand evolution and generation aging.

4. **Converters and transmission losses and efficiencies**: The model consider power conversion from the electricity generation side, however it does not take into account the power conversion and losses needed for electricity transmission. Additionally, the grid size as well as the distance between generation and consumption is not considered. The consequence is that in reality, the needed generated electricity as well as the total cost of the system could be higher than what is calculated by the model.

5. **Grid stability**: The model by being evaluated at hourly time steps, does not take into account sub-hour variability of demand and generation. As a result, the deployment of technologies needed to guarantee the stability of the system under this sudden changes are not determined. However, the importance of the stability of the grid, particularly of the frequency control is acknowledged in the model and considered by means of spinning reserves.
5.4 Model Inputs

The inputs required by the model depicted in Figure 5.15 fall into three main categories: island data, options selection and installed units/capacity.

5.4.1 Island Data

Meteorological Data

The meteorological data described in Chapter 4 provide the information necessary to determine the electricity generation potential of the renewable energy technologies. The data needs to be supplied as timeseries in hourly time steps.

Assumptions

- The sub-hour variability usually present in resources as wind speed, irradiation and waves are not taken into account.
- As the meteorological data was obtained from different sources, any possible correlation between them is not taken into account. However, statistical typical year-like data was used to evaluate the general potential of each place and avoiding good/bad year circumstances.
- If information for a resource is not available, the model interprets it as a zero potential, discarding from the beginning the associated technology.

Demand Data

The demand, as the meteorological data, needs to be input as timeseries in hourly time steps.

Assumptions

- The sub-hour variability of the demand as well as its real time unpredictability are not taken into account.

Socioeconomic Data

Information regarding the population of the island, the island electricity generation configuration and the GDP per capita is needed.

Assumptions

- The population remain as a constant for the whole year. This is important because the increase in population, mainly in the touristic season, is not taken into account for the calculations of domestic heat electrification and cooling. Nevertheless, the effect of tourism on the load (if existent) is already considered in the demand profile to some extent.
5.4.2 Options selection

The model considers different possibilities regarding technologies to be used. It includes:

1. 2 PV panels - JA Solar JAP6 280Wp polycrystalline, jinko Eagle Plus 72 360 Wp polycrystalline*.
2. 4 wind turbines - Gamesa 2MW, Gamesa 2.5MW, Enercon 2.3MW, Gamesa 4.5MW*
3. 5 WECs - Pelamis*, Oyster, Wave Dragon, SSG, Aqua Buoy.
4. 1 tidal current turbine - Tocardo T2*.
5. 2 battery technologies - Lead acid and Li-ion (Tesla’s Powerpack* and Powerwall).
6. 1 OTEC*.
7. 1 OTEC-SWAC configuration*.
8. Biodiesel generation*

It is important to note that the technologies marked with * are the ones used for generating the results in Chapters 7 and 8.

Additionally, the model counts with the flexibility to specify if the residential heat sector and/or the cooling sector are to be considered in the simulation.

5.4.3 Installed units / capacity

The last input of the model is the amount of units installed (for PV, WT, OTEC, Tidal, WEC and battery) and the total capacity of the biodiesel generators.

5.5 Selected technologies

In this section the models describing each of the technologies included in the model are explained. For more information regarding the governing principles of each technology refer to the background subsection.

PV

Being, along with wind turbines, the most mature and widespread technologies, they were included in the model. The electric generation of a PV system depends as described before, on the irradiance ($G_M$), the panel efficiency ($\eta_{mod}$), the temperature of the module ($T_m$) and the efficiency of the BoS ($\eta_{BoS}$) as modeled and described in [43].

$$T_M = T_a + \frac{T_{NOCT} - 20^\circ C}{800} \cdot G_M \left( \frac{9.5}{5.7 + 3.8 \cdot w} \right) \left( 1 - \frac{\eta_{cell}}{T \cdot \alpha} \right)$$ (5.11)
The module temperature can be modeled by the Duffie-Beckman model as described by eq. 5.11 where $T_a$ is the ambient temperature, $T_{NOCT}$ the nominal operation cell temperature, $w$ the wind speed and $T \cdot \alpha$ is the fraction of the light absorbed by the solar cells, normally assumed to be 0.9.

Additionally, the effect of solar irradiance needs to be taken into account as the performance of PV panels vary with the amount of power reaching the modules.

$$ FF = \frac{V_{mpp} \cdot I_{mpp}}{V_{OC} \cdot I_{SC}} $$ \hspace{1cm} (5.12)

$$ FF_{GM} = FF_{NOCT} + \left( \frac{FF_{STC} - FF_{NOCT}}{1000 - 800} \right) (G_M - 800) $$ \hspace{1cm} (5.13)

$$ V_{OC}(25^\circ C, G_M) = V_{OC}(STC) + \frac{n \cdot k_B \cdot 298.15}{q} \ln \left( \frac{G_M}{1000} \right) $$ \hspace{1cm} (5.14)

$$ I_{SC}(25^\circ C, G_M) = I_{SC} \cdot \left( \frac{G_M}{1000} \right) $$ \hspace{1cm} (5.15)

$$ P_{MPP}(25^\circ C, G_M) = FF_{GM} \cdot V_{OC}(25^\circ C, G_M) \cdot I_{SC}(25^\circ C, G_M) $$ \hspace{1cm} (5.16)

$$ \eta_{mod}(25^\circ C, G_M) = \frac{P_{MPP}}{G_M \cdot A_M} $$ \hspace{1cm} (5.17)

Where $FF$ is the fill factor, $I_{MPP}, V_{MPP}, P_{MPP}$ are current, voltage and power at the operating maximum power point and $I_{SC}, V_{OC}$ the short circuit current and open circuit voltage respectively.

Then, the module efficiency can be calculated for any instance in time taking into account the actual conditions at which it is operating by:

$$ \eta_{mod}(T_M, G_M) = \eta_{mod}(25^\circ C, G_M) \cdot [1 + \kappa \cdot (T_M - 25^\circ C)] $$ \hspace{1cm} (5.18)

$$ \kappa = \frac{1}{\eta_{mod}(STC)} \cdot \left( \frac{\partial \eta}{\partial T} \right) $$

Where $\frac{\partial \eta}{\partial T}$ is the efficiency temperature coefficient.

Finally, the power generated by the AC power generated by the PV module is:

$$ P_{PV} = A_M \cdot G_M \cdot \eta_{mod}(T_M, G_M) \cdot \eta_{BoS} $$ \hspace{1cm} (5.19)

$$ \eta_{BoS} = \eta_{inverter} \cdot \eta_{MPPT} \cdot \eta_{other} $$

The parameters of the selected panels were obtained from SNF Solar [88].

Assumptions

- The equations used to describe $T_M$ are dependent on the type of mount of the PV modules and were developed for roof installations. However, this approach is appropriate and even conservative as PV in utility installations have more distance between the panel and the surface upon which they are mounted, allowing more air to flow and therefore decreasing the estimated module temperature.
The model considers a fixed tilt angle of the module. The angle chosen for each island is such that it maximizes the irradiance per square meter in a year and it is site dependent as shown in page 39. This angle is indirectly considered in the model as the irradiance values of each island retrieved from Meteonorm are corrected to the optimum tilt angle.

Wind Turbines

The modeling of the wind turbines was done using the power curve of specific wind turbines available\cite{89}. This was done so all the losses happening in the power conversion are taken into account. As described before, a power curve uses as input the wind speed at hub height and delivers the power generated by the turbine at that speed following the curve. Figure 5.16 shows the power curve of a 2.3MW Enercon wind turbine.

Usually, the hub of the wind turbine is much higher than where the measuring was done, so measured wind speed needs to be corrected. This can be done in 2 steps as proposed by professor Michiel Zaaijer in the course Introduction to Wind Energy. From 0 - 60m the logarithmic law applies (eq. 5.20) and after 60m the power law (eq. 5.21) holds.

\begin{align*}
U(60) &= U(h_{ref}) \cdot \frac{\ln \left( \frac{60}{z_0} \right)}{\ln \left( \frac{h_{ref}}{z_0} \right)} \\
U(h_{hub}) &= U(60) \cdot \left( \frac{h_{hub}}{60} \right)^{\alpha}
\end{align*}

Where $U$ is the wind speed, $z_0$ \cite{90} the surface roughness length and $\alpha$\cite{91} a friction coefficient. Both the surface roughness length and the friction coefficient are a measure of the landscape where the measurement was taken and for a landscape with crops, hedges and shrubs the value for both is 0.2.

Assumptions
• The dynamics of sub hourly phenomena such as sudden wind gusts and wind turbine inertia are not considered as the output is an average of the wind speed through the whole hour. Additionally, due to the hourly time step it is assumed that the output of the turbine can vary from 0 to rated power in one hour.

Wave Energy Converters

An important objective of this thesis is to evaluate the performance and role that ocean technologies can play within a HRES, thus WEC, tidal current and OTEC are included. As described previously, WECs differ greatly on their working principles and models simulating their performance are not available. For that reason, it was chosen to model the WECs using their power matrices. In this way, the approximate power that the WEC would deliver can be estimated from known data of height ($H_s$) and period conditions ($T_e, T_z, T_p$). Power matrices for WECs are difficult to find, but examples can be sorted from the literature [77, 92]. Figures 5.17a, 5.17b shows the power matrices of an Aqua Buoy WEC and a Pelamis WEC.

![Power Matrix - AquaBuoy](image1)

![Power Matrix - Pelamis](image2)

(a) Aqua Buoy WEC
(b) Pelamis WEC

Figure 5.17: Power curves of Wave Energy Converters

Assumptions

• As with the wind turbine, the sub hour changes in ocean conditions that can affect the WEC performance are not considered, and an average of the production of an hour is used.

Tidal Current Turbines

Following the description presented previously, the power performance of tidal turbines is very similar to that of wind turbines. The power curve was constructed using eq.5.4. A Tocardo T2 turbine is used as proposed by [5]. This turbine can have different blade lengths suitable for different current speeds. The blade length corresponding to the lowest rated current speed was selected to produce even in the least favorable conditions. [93] The parameters used to model the power curve are shown in Table 5.2 and the resulting power curve.
Assumptions

- The main assumption is that the T2 turbine can be installed and generate power in all of the proposed locations.

Ocean Thermal Energy Conversion (OTEC)

OTEC technology has the potential to become a baseload generation technology. As shown in the background section, the electrical power generated by an OTEC plant can be calculated by eq.5.10. The equation can be modified to depend on the the plant’s nominal capacity. With information provided by Bluerise on plant capacity and flowrates, the power generated by an OTEC plant can be modeled as proposed by [80]:

\[
P_{OTECC} = \frac{3 \cdot Cap \cdot Q_{ww} \cdot \rho_w \cdot c_p \cdot \eta_f \cdot \psi}{16 \cdot (1 + \psi) \cdot (T_{surf} + 273.15) \cdot (T_{surf} - T_{deep})^2} - 0.3 \cdot \Delta T^2_{design}
\]

Where:
Cap: installed capacity [W]
$Q_{ww}$: Warm water flow rate per $W$ capacity $[m^3/sW]$
$ho_w$: Density of seawater $[kg/m^3]$
$c_p$: heat capacity of seawater $[J/kg \cdot K]$
$\eta_T$: efficiency of the turbine
$\psi$: Ratio of cold seawater flow rate over warm sea water flow rate
$T_{surf}$: Surface water temperature $[^\circ C]$
$T_{deep}$: Deep water temperature $[^\circ C]$
$\Delta T_{design}$: Design temperature difference $[K]$

The parameters used in the model are summarized in Table 5.3.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Cap$ $[kW]$</td>
<td>5000</td>
</tr>
<tr>
<td>$Q_{ww}$ $[m^3/skW]$</td>
<td>0.003</td>
</tr>
<tr>
<td>$c_p$ $[J/kg \cdot K]$</td>
<td>4000</td>
</tr>
<tr>
<td>$\eta_{turbine}$</td>
<td>0.85</td>
</tr>
<tr>
<td>$\psi$</td>
<td>0.5</td>
</tr>
<tr>
<td>$\Delta T_{design}$</td>
<td>20</td>
</tr>
</tbody>
</table>

Assumptions

- The power of the OTEC plants only depend on the ocean’s temperature difference, as all the other parameters are kept constant. This means, that the effect of varying flow rate to control power output is not considered.
- The parasitic power consumption caused by the seawater pumps does not vary with varying ocean’s temperature difference. As a result, a decrease in the surface temperature has a decrease in the power generated by the plant but not on the water pumped, and thus the power consumption of the pumping system is constant.

Fuel Generators

Fuel based generators were modeled as dispatchable sources. In the model a distinction is made between conventional generators (mainly diesel and heavy fuel oil (HFO) based) and generators which can be fueled by biodiesel.

Conventional - Diesel/HFO

The conventional generators, diesel mainly in small islands, but a combination of fuels in big systems, are modeled allowing them to provide all the electricity that is needed to meet the demand. The amount of electricity generated by the conventional generators is determined by the control logic and as can be expected is the last source to be used. Although performance based fuel usage models are available for diesel generators, they were not used due to two main reasons: 1) All the conventional generators are effectively modeled as one big
generator with the capability to satisfy the peak demand of the island and provide the required spinning reserves, thus no real parameters exist for a generator of that size suitable for the equation. 2) In reality, the generators are a combination of various fuels, mainly diesel and HFO and cannot be modeled only as a diesel generator. Instead, it was decided to use average fuel costs of generation for each island. This was done by dividing the total expenditure in fuel for electricity generation over the total electricity generated by the conventional generators.

Assumptions

- The already installed capacity of the conventional generation is that of the peak demand plus the spinning reserves required.
- The generators can provide all the power required. Thus, they are not constrained by ramp-up and ramp-down values. This assumption was made because: 1) it is assumed that the hourly time steps are enough for any change in power output and 2) the modeled generator in reality is a combination of various different size equipments which currently are able to supply the load with reliable power.

Biodiesel

Similar to the conventional generators, the biodiesel generators were modeled as dispatchable source with the capability of providing any power output at every time step. However, the generation of electricity is constrained by the installed capacity.

Assumptions

- The generators can go from zero to rated power at any given time step.
- Biodiesel is considered to be land based (average between rapeseed and sunflower) for land usage calculations. [94]

Energy Storage - Batteries

Batteries were the only storage technology selected for the system. Although, as explained in the background, there are other types of storage suitable for renewable energy integration as pumped hydro[4], they largely depend on the specific characteristics of the islands. Batteries, on the other hand, can be installed virtually everywhere, which is appropriate for this model that attempts to be general for every possible island. Additionally, batteries can provide various services to the electricity systems as shown by [9] such as voltage support and ancillary services.

Two technologies were included in the model, lead-acid and Li-ion batteries. The former because of the maturity and cost of the technology, and the latter because of its reliability and increasing production which has seen a huge decline in its costs. As the model is evaluated every hour, neglecting all the sub-hour phenomenons and thus, the dynamic behavior of the systems, the battery model was simplified as well. As shown by Figures 5.13 and 5.14a, essentially both battery technologies are charged in a stages to increase their lifetime. During those stages, the SOC of the battery increases in a logarithmic way and can be approximated in a linear way, in this model it is approximated by two lines.[5, 4]. The main difference however, is the time each stage takes,
being reasonably longer in lead-acid batteries. For lead-acid batteries, the 1st stage lasts between 5-7 hours and charges typically to 70% and the second stage takes between 7-10 hours to charge the other 30%. If we consider the first stage to take 5 hours and the second stage to take 8, this means that effectively in the first stage a charge rate of 0.14C is used and 0.0375C in the second stage. For Li-ion batteries, it can be seen from Figure 5.14a that typically the charge of a battery takes 3 hours of which stage 1 takes 1 hour. From Figure 5.14b, it can be seen that at 1 hour the battery is charged to 80% and then charged to 100% in the next two hours. This means, that even though the battery can handle higher power flows, it is going to be charged at approximately 2/3 of its maximum power, which is lower than the charge rate of 0.8C deduced from figure 3. Taking this into account, whenever information was available from the manufacturer about the battery’s charge rate, that information was used. If not, the maximum value between the deduced charge rates from the figures and the approximation of 2/3 of the battery’s maximum power, was used as the charge power. Additionally, the maximum power of the battery was used as the limit of discharge. Furthermore, the battery’s reported round trip efficiency was considered as well as the depth of discharge recommended by the manufacturer. Figures 4 and 5 show the two stage charge approximations of a Li-ion Tesla Energy Powerwall(95) and a lead-acid battery (83).

\[
\begin{align*}
\text{(a) Lead-acid} & & \text{(b) Powerwall} \\
\text{Figure 5.19: Charging profiles of lead-acid and Li-ion batteries}
\end{align*}
\]

Assumptions

- An initial SOC equal to \( \text{SOC}_{\text{min}} \) is assumed in the model.
- The effect of discharge rate in the battery capacity is not considered. As stated before, the battery capacity decreases with increasing discharge rates. However it is assumed that at the maximum nominal output of the battery, the rated capacity is not drastically decreased.
- The effect of charge rate in the battery life of the battery was not directly taken into account. However, by limiting the rate of charge to either the charge recommended by the manufacturer or 0.8C / 0.14C, it is assumed that no degradation of the battery is forced [87] and thus, no decrease in the lifetime.
• The charge and discharge efficiencies were approximated as $\sqrt{\frac{\text{Roundtrip}}{\eta}}$ [96].

• The temperature effects on the capacity and lifetime are not taken into account, thus assuming that the batteries are always operated at 20°C which is considered the optimum service life of batteries. [97]

5.6 Control Strategy

A simple control strategy based on the *load following* strategy proposed by [98] is used. In this control strategy the conventional generators are never used to charge the battery. Furthermore, the power dispatch is done by means of a merit order table in which batteries have the priority, then biofuel generators and last conventional generators. Additionally, a spinning reserve constraint is added at the end of the control strategy to guarantee that there is always available capacity to comply with this stability measure as done by [7]. Figure 5.20 shows the control strategy used in the model.

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plen = Plch</td>
<td>Plen = Plch</td>
</tr>
<tr>
<td>Plen = Plch</td>
<td>Plen = Plch</td>
</tr>
</tbody>
</table>

Figure 5.20: Control strategy
5.7 Residential Heat Demand: Hot water and cooking

The effect of the electrification of the residential heat sector was modeled based on the information obtained from the 2015 ATUS explained in Chapter 3. The probability distributions for showering and cooking were estimated from the ATUS data.

The energy consumed by either activity throughout a day can be calculated by eq. 5.23:

\[ E(t)_a = p_a(t) \cdot \text{population} \cdot t_{act}(t) \cdot E_{s_{act}} \] (5.23)

Where:
- \( E(t)_a \): the energy consumed by activity \( a \) in a simulation time step.
- \( p_a(t) \): the probability distribution of activity \( a \).
- \( \text{population} \): is the total population of the island.
- \( t_{act}(t) \): is the distribution of duration of activity \( a \).
- \( E_{s_{act}} \): is the specific energy consumption of activity \( a \).

To estimate the electricity energy demand, cooking stoves were the only technology considered as it is the most common technology used for preparing everyday meals. The specific energy consumption was estimated based on the reported energy consumption of an Ecuadorian dish on electric stove, with a value of 0.015 kWh/min for a meal for 1 person from [18], who did a study on the performance of different cooking stoves. The value is in the range of what [19] reported. Additionally, the time distribution for cooking was derived from the ATUS data. The specific energy consumption for hot water was modeled considering that most of the hot water is for showering. Typically, water is heated to 60°C even if it is used at lower temperatures for health reasons. [37] The electricity needed to heat the water is given by

\[ E_{\text{hotwater}} = \frac{\rho_{\text{water}} \cdot Q_{\text{water}} \cdot c_p \cdot (T_{hot} - T_{cold})}{EF} \] (5.24)

Where:
- \( \rho_{\text{water}} \): density of water.
- \( Q_{\text{water}} \): volumetric flow rate.
- \( c_p \): specific heat of water.
- \( T_{hot} \): hot water temperature. (60°C)
- \( T_{cold} \): cold water temperature.
- \( EF \): Energy factor of the electric water boiler.

Assumptions

- The probability distribution created from the ATUS dataset for cooking and showering is assumed to be representative for all islands. In reality, habits vary between regions and nations, which may cause that the peaks to shift by a couple of hours.

- The energy consumption required for cooking is based on the energy needed for a standard Ecuadorian dish [18] which is assumed to be representative of the energy consumption by an average dish in the selected places. Additionally it is assumed that on average, a person cooks meal for 2 people.
• The average showering time is kept constant throughout the day and is assumed to be 8.2 minutes. \[^{33}\]

• The feed temperature of the water to the water heater is assumed to be the yearly mean temperature.

• The shower flow rate is assumed to be 2 gallons per minute, which is equivalent to the water saving shower head label of the EPA \[^{99}\] and the \( EF \) 0.95 based on the standard set by the US Department of Energy. \[^{100, 101}\]

• It is assumed that all the energy from cooking and water heating of the selected (tropical) islands come from fossil fuels. Thus, a zero electrification of this appliances is considered. \[^{102}\]

5.8 OTEC-SWAC cooling potential

The OTEC-SWAC cooling potential is calculated using the service sector cooling loads explained in Chapter 3 and a modified OTEC model which includes a seawater air conditioning plant in parallel configuration. Parallel configuration was chosen because it allows operation flexibility for the OTEC-SWAC plant, allowing the OTEC plant to run at 100% when cooling is not needed and decrease its electricity output to provide cooling power to cover the service sector cooling demand. A schematic of the OTEC-SWAC configuration can be seen in Figure 5.21. It is important to note that a series or cascade configuration could also be possible, but it would require a lower cold water outlet temperature from the OTEC unit which implies an even larger volumetric flow rate (and thus, a bigger cold water pipe).

In the OTEC-SWAC model it is considered that the OTEC capacity is 5000 kW and that the minimum power output is 70% of its nominal capacity. As a consequence, each OTEC-SWAC plant has a cooling capacity of 64 MW\( t \). The electricity output of the OTEC-SWAC is determined by the cooling demand. The OTEC-SWAC plant will cover the cooling demand up to its maximum capacity by using up to 30% of the nominal cold water flow rate. The cooling power can be calculated by:

\[
Q_{cw} = Q_{cwSWAC} + Q_{cw - QcwSWAC} \]

\[
Q_{cwSWAC} = Q_{cw} \times \frac{QcwSWAC}{Qcw} \]

\[
Q_{cw - QcwSWAC} = Q_{cw} - Q_{cwSWAC} \]

Figure 5.21: OTEC-SWAC plant in parallel configuration.
\[ P_{\text{SWAC,th}}(t) = \rho \cdot c_p \cdot Q_{\text{csw,SWAC}}(t) \cdot (12^\circ - T_{\text{deep}}(t)) \]  

(5.25)

Where \( Q_{\text{csw,SWAC}} \) is the cold water required by the SWAC unit in \([\text{m}^3/\text{s}]\). The cold water required can be calculated as:

\[ Q_{\text{csw,SWAC}}(t) = \frac{P_{\text{cool}}(t)}{\rho \cdot c_p \cdot (12^\circ - T_{\text{deep}}(t))} \]  

(5.26)

and limiting the maximum flow rate to 30% of the nominal cold water flow rate such that if \( Q_{\text{csw,SWAC}}(t) > 0.3 \cdot \psi \cdot Cap \cdot Q_{\text{ww}} \) then, \( Q_{\text{csw,SWAC}}(t) = 0.3 \cdot \psi \cdot Cap \cdot Q_{\text{ww}}. \)

The OTEC unit adjusts the hot water consumption to the available cold water and determines the electricity produced using eq. 5.22 A 15% of the electricity that would have been needed to provide \( P_{\text{SWAC,th}} \) is deducted from the OTEC electricity produced as it is required in the SWAC unit (mainly for pumps). [103]

To estimate the effect of OTEC-SWAC cooling on the electricity demand, the total service sector cooling demand is evenly distributed among the installed OTEC-SWAC plant. Then, once the cooling power per OTEC-SWAC plant is computed, the amount of the cooling demand covered is determined. Under the assumption that currently this needed cooling power is provided with electricity via air conditioning units, the amount that is covered by OTEC-SWAC is considered an electricity saving decreasing the electricity demand and modifying the electricity profile as follows.

\[ E_{\text{elecsaved}}(t) = \frac{P_{\text{cool}}(t) - P_{\text{SWAC,th}}(t) \cdot X_{\text{OTEC-SWAC}}}{SEER} \]  

(5.27)

\[ E_{\text{demand}}(t) = E_{\text{demand,initial}}(t) - E_{\text{elecsaved}}(t) \]  

(5.28)

Assumptions:

- The OTEC-SWAC plant can change the output power of its units between the maximum and minimum within 1 hour. This means that the OTEC unit can adjust its operation between 70% and 100% and the SWAC unit between 0 and 100%.

- The SWAC plants operates with a fixed output cold water temperature of 12°C as suggested in [17]

- Current cooling demands are provided using electric air conditioners.

- It is the case that currently SWAC applications are economically more feasible than OTEC or hybrid OTEC-SWAC plants. With advise from Bluerise, a 70% minimum output is considered to guarantee the economic feasibility of the OTEC unit as it is of interest to explore the role of this hybrid OTEC-SWAC configuration.
5.9 Model additions

As stated previously, this model was developed based primarily on the work of van Velzen [5]. The main modifications and additions to the original model are:

- The inclusion of biodiesel and OTEC-SWAC as generating technologies.
- The possibility to simulate demand modification scenarios.
- The consideration of spinning reserves for stability purposes.
- The migration from an island specific code to a function based general model easily applicable to multiple islands.
- Automatic estimation of upper bounds for the selected technologies.
- The addition of objective functions selection for sequential model evaluation.
Chapter 6

Optimization

In order to find the optimal configuration of a HRES on a given island, it is necessary to couple the model described in Chapter 5 with an optimization algorithm and formulate the optimization problem to solve. In it, the objectives that want to be achieved and upon which the configuration of the HRES is going to be optimized are defined. For this thesis, the Matlab `gamultiobj` solver (an NSGA-II algorithm) is used because of the ability of genetic algorithms to deal with multiobjective optimization problems and to find global optimums. This chapter is divided in 3 sections. The first one will provide a brief theoretical background regarding genetic algorithms. In the second section the problem formulation is stated with the description of the decision variables, objective functions, constraints and information about the chosen algorithm. Finally, the third section presents the cost data and assumptions used in the optimization.

6.1 Background

Optimization Algorithms for HRES

As shown previously in the literature review, there are various possibilities on the choice of optimization algorithms for the sizing of a HRES. Meta heuristic algorithms, both trajectory based and population based, are commonly used due to their ability to cope with complex problems. In particular, genetic algorithms (GA) have been used and proved to be efficient in solving multiobjective optimization for the sizing of HRES.[12, 104] The main advantage of GA in multiobjective optimization is the fact that the objective functions are considered independently without the need to combine them via a weighted sum in a single objective function. As a consequence, the result is a set of optimal solutions (Pareto optimal solution set), whereas with classical algorithms with weighted objective functions the solution is a single point. It is evident from this difference that the Pareto optimal solution set provide different optimal solutions representing the tradeoffs between the objective functions and that additional high level information is needed to choose one of the optimal solutions. It is important to add, however, that in the Pareto optimal set none of the solutions is more optimal than the other.[105]
Genetic Algorithm

The genetic algorithm is an evolutionary based algorithm. In other words, it uses evolutionary principles as (population, reproduction, crossover and mutation) to search for the optimal solution. In general, evolutionary algorithms are preferred for multiobjective optimization for three main reasons:

- Do not require derivative information.
- Simplicity of implementation.
- Flexibility and wide range of applicability.

Additionally, the random, probabilistic nature of the GA search allows the possibility of parallel search and finding the global optimum.

The GA is constructed analogous to evolutionary theory. The algorithm starts by creating, using a creation function, a population - a set of chromosomes (candidate solutions) which are conformed by genes (decision variables). The population is then evaluated with a fitness function (the multiobjective function) and the chromosomes are ranked according to their fitness value; the chromosomes with the best fitness value are better solution candidates and should be the more apt to survive forming the non-dominated front. After the chromosomes are ranked, a selection function chooses the parents for the new generation forming the mating pool. Then, gene exchange occurs among the parents via a crossover function creating the offspring of the new generation. Finally, due to the fact that all of the offspring are created from the parents set, diversity is added (randomly) to the population via the gene mutation function. These steps are repeated iteratively for an i number of generations until the Pareto optimal set is found. Figures 6.1 and 6.2 show the algorithm of the GA and the scheme of crossover and mutation processes respectively.

![Figure 6.1: Genetic Algorithm flowchart](image)

To have a better understanding on how the new generations are created in the GA the most important concepts and functions are explained below:
Decision variable space and solution space: multiobjective optimization has the characteristic that two search spaces exist: decision variable space and solution space. The decision variable space is defined by the $n$ decision variables ($\mathbf{x} = (x_1, x_2, ..., x_n)^T$) of the problem and has a dimension of $\mathbb{R}^n$. The solution space depends on the multiobjective function with $M$ objectives ($f(\mathbf{x}) = \mathbf{z} = (z_1, z_2, ..., z_M)^T$) and has a dimension of $\mathbb{R}^M$. The optimal solution is a set $\mathbf{Z}_{\text{Ps}} \subseteq \mathbb{R}^M$ of non-dominated solutions $\mathbf{z}_{\text{opt}}$, called the Pareto optimal solution set or Pareto front. From Figure 6.3 it can be seen that every feasible combination in the decision variable space can be mapped to the solution space, nevertheless, the boundaries and shape are not the same. [105]

Dominance: As can be seen from Figure 6.3 not all solutions of the solution space are optimal. To find them, it is necessary to have a way of comparing them to find the best. This is done with the concept of dominance. If a solution $\mathbf{z}_a$ is better in all objectives than $\mathbf{z}_b$ it is said that
solution $z_a$ dominates $z_b$. However, if a solution $z_a$ is better than $z_c$ in one objective but worse in the other they are called non-dominated solutions (with respect to each other). Formally, it can be said that solution $z_a$ dominates $z_b$ if the following conditions are true: [105, 106]

1. Solution $z_1$ is no worse than $z_2$ in all objectives.
2. Solution $z_1$ is strictly better than $z_2$ in at least one objective.

**Non-dominated front**: is the set of solutions ($Z_{nd} \subset Z_a$) which dominates the rest of the solutions in solution set $Z_a$ but that are not dominated between them. In other words, for any solution outside of $Z_{nd}$ there is an element $z^* \in Z_{nd}$ that will dominate it. Thus, the main property of the non-dominated front is that it dominates the rest of the solutions meaning that they are better solutions compared with the rest. When the solution set $Z_a$ is the whole solution space, then $Z_{nd} = Z_{Ps}$ and is called the Pareto optimal set. [105]

**Non-dominated sorting**: for some GA such as the non-dominated sorting genetic algorithm II (NSGA-II) it is necessary to order the population in different levels or fronts of non-domination. To do so, the non-dominated set of the whole population is found. Because this set dominates the rest of the population it is the best non-dominated set and is called non-dominated solutions of level 1 or first non-dominated front. Furthermore, this set is temporally removed of the population and another (second) non-dominated set is found called non-dominated solutions of level 2. These algorithm is done iteratively until all solutions are classified in non-dominated levels. It is important to note that in the worst case scenario there can be as many non-dominated fronts as members of the population. [105]

**Creation function**: its main objective is to create the initial population within the specified bounds of each decision variable. These can be done by evenly distributing the decision variables on its bounds or randomly.

**Selection function**: Its objective is to create a new generation based on the best chromosomes of the population. To do so, it focuses on 3 main aspects [105, 8, 107]:

- Identify good chromosomes in the population.
- Make multiple copies of good chromosomes.
- Eliminate bad chromosomes from the population.

There are two common methods used: tournament selection and proportionate selection. In the former a certain amount of parent candidates are chosen randomly from the population and based on their fitness function value one is selected (wins), while in the latter also called roulette wheel selection each parent has a slice of the roulette proportional to its relative fitness value and as a consequence more chance of being selected.

**Crossover function**: Along with the mutation function their main objective is to create new offsprings. The crossover operator typically picks randomly two parents and create an offspring by exchanging genes. Crossover occurrence is determined by a crossover probability $p_c$. Similar to the selection function, various methods are available in the literature such as the single crossover, linear crossover, simulated binary crossover, to name a few. [105]
6.1. Background

**Mutation function:** As can be seen, the crossover generates the *offsprings* from their parents but cannot introduce new *genes* to the population. The mutation’s main objective is to add diversity to the population by perturbing the *offspring* in the vicinity of the decision variables. Mutation occurs with a probability $p_m$ that is usually small enough to keep good *chromosomes* but enough to provide diversity. Some of the available methods are random mutation, normally distributed mutation and non uniform mutation. [105] For instance, Matlab’s `gamultiobj` routine uses gaussian distribution to perform the mutation. For each gene, the mean is set to 0 and the standard deviation is shrinked recursively after each generation to reduce size of the applied perturbation.

**NSGA-II**

The NSGA-II is a modified GA created in 2001 by Kalyanmoy Deb and his students. [108] The algorithm objective is to find multiple Pareto optimal solutions and has 3 features:[106]:

- Uses an elitist principle which causes that the “population best solutions cannot degrade with generations”. [105]
- Uses an explicit diversity preserving mechanism
- Emphasizes non-dominated solutions.

By doing this, the NSGA-II can preserve good *chromosomes* found throughout the iterations while preserving enough diversity to find new solutions and have a well distributed Pareto optimal set.

The elitism operator used in the NSGA-II is the *fast non dominating sorting approach*. In it, the *parents* are allowed to compete with the *offsprings* to generate the new population. Both *parents* and *offsprings* sets are combined and then they are sorted into their various non-dominated fronts. The new population is filled by adding the non-dominated fronts one at a time. First, the first non-dominated front is added. If the space left in the population is more than the size of the complete second non-dominated front it is added. This is done iteratively until the next non-dominated front cannot fit entirely in the population. At this moment, the diversity preserving operator, the *crowding distance sorting*, is used. The *crowding distance sorting* aims to preserve diversity by preserving the solutions of the last non-dominated front considered that are located in the least dense areas of the front. To do this, the *crowding distance* which is an “estimate of the perimeter of the cuboid formed by using the nearest neighbors as the vertices”, is calculated. [108]

Evidently, the remaining fraction of the population is filled with the *chromosomes* which have the biggest *crowding distance* values. The crowding *distance calculation* and the creation of the new population is shown in Figures 6.4a and 6.4b respectively.
Chapter 6. Optimization

(a) Crowding distance calculation. [108]  
(b) NSGA-II procedure. [108]

Figure 6.4: Crowding distance and new population creation in the NSGA-II algorithm.

6.2 Problem Formulation

To determine the cost-optimal configurations of the island’s HRES and understand how they vary with increasing renewable energy integration, a multiobjective optimization problem is proposed. In it two objective functions, one evaluating the cost of the system and the other evaluating the coverage of renewable energy are used. The goal of the optimization is to minimize the cost of the system while maximizing the coverage of renewables.

6.2.1 Objective Functions

1 - Levelized Cost Of System (LCOS)

There are various cost objective functions used in the sizing of HRES being the levelized cost of electricity (LCOE) one of the most common. [12] The LCOE is a measure of the electricity cost (in \$USD/kWh) generated by a given plant. It is calculated taking into account all the expected lifetime costs (capital costs, fuel costs, operation and maintenance, financing costs and incentives) and dividing it by the electricity generated over the lifetime. As the LCOE is calculated for an estimated lifetime, the costs are discounted in order to account for the time-value of money. [109] The LCOE can be interpreted as the price at which electricity needs to be sold for the project to break even. It is important to note that for the case of electricity systems, the costs of the technologies are divided by the total electricity demand of the year instead of the power generated by the technologies.

The LCOE calculation can be extended to account for the storage technologies present in a HRES becoming the levelized cost of system (LCOS). However, in this thesis LCOS and LCOE will be used indifferently. A simplified LCOS was chosen for this thesis as the cost objective function. The LCOS is calculated as follows:

$$\text{LCOS} = \frac{\sum_{t=1}^{t_{LT}} \left( \sum_{j=1}^{N_T} I_{t,j} + O_{t,j} + M_{t,j} + F_{t,j} \right) (1+i)^t}{\sum_{t=1}^{t_{LT}} E_{d,t}(1+i)^t}$$  \hspace{1cm} (6.1)
6.2. Problem Formulation

Where:

- **LCOS**: Levelized cost of system [USD/kWh]
- **I<sub>t,j</sub>**: Investment of technology **j** in year **t** [USD]
- **O&M<sub>t,j</sub>**: Operation and Maintenance cost of technology **j** in year **t** [USD]
- **F<sub>t,j</sub>**: Fuel cost of technology **j** in year **t** [USD]
- **E<sub>d</sub>**: Total electricity demand of year **t** [kWh]
- **t<sub>LT</sub>**: Project lifetime years
- **NT**: Is the total number of technologies in the HRES
- **i**: Discount rate or weighted average cost of capital (WACC)

Furthermore, it is important to mention that the LCOS calculation does not take into account costs related to transmission, distribution and power quality which are relevant when analyzing all the costs associated with a reliable energy system.

**Assumptions**

- Lifetime of the HRES is assumed to be 20 years.
- The components conforming the HRES are all installed in the first year.
- The investment for the conventional generation is considered to be 0. The reason is that in all the islands it is assumed that a capacity equal to 1.2 times the peak demand is already installed (corresponding to the peak demand + spinning reserves).
- The WACC is assumed to be 10% reflecting the perceived risk of energy projects in non OCDE countries. [110]
- Batteries are assumed to be replaced every 5 years or when their maximum cycles are reached.
- The energy production of a year considered (**E<sub>t</sub>**) is not the total energy produced by the system, but only the amount of energy that is needed (and therefore can be sold).

**2 - Coverage**

The second objective function, which is related to the renewable energy integration, is the **coverage**. The coverage is the fraction of the demand that is provided by renewable energy technologies. At any given moment, the required electricity (**E<sub>demand</sub>**) is provided by a combination of fuel based generation (**E<sub>FG</sub>**) and renewable energy (**E<sub>RE</sub>**).

\[
E_{\text{demand}} = E_{\text{RE}} + E_{\text{FG}}
\]  \hspace{1cm} (6.2)

The coverage aims to measure the capacity of the system to provide “useful” renewable electricity. It is defined as:

\[
\text{Coverage} = \frac{E_{\text{RE}}}{E_{\text{demand}}}
\]  \hspace{1cm} (6.3)
Analogously, the coverage can be written in terms of the energy provided by the conventional generators as:

\[ \text{Coverage} = 1 - \frac{E_{FG}}{E_{\text{demand}}} \]  

(6.4)

It is worth noting that maximizing the coverage is equivalent to minimizing the fuel based generation electricity.

### 3 - Lifecycle CO\(_2\) (eq) emissions

This third objective function is used in Chapter ??, and, as its name suggests, it allows to design a system in which the total lifecycle emissions of the selected technologies are minimized. The total emissions can be calculated as the product of the functional unit times the emission factor.

\[ M_{CO_2} = \sum_{i=1}^{n} e_{f_i} \cdot F U_i \]  

(6.5)

The emission factors various technologies are given in Table 6.1.

**Table 6.1**: Emission factors for chosen technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Emission Factor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel</td>
<td>945 g/kWh</td>
<td>[111]</td>
</tr>
<tr>
<td>Heavy Fuel Oil</td>
<td>850 g/kWh</td>
<td>[111]</td>
</tr>
<tr>
<td>Natural Gas</td>
<td>500 g/kWh</td>
<td>[111]</td>
</tr>
<tr>
<td>Coal</td>
<td>1000 g/kWh</td>
<td>[111]</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>360 g/kWh</td>
<td>[111]</td>
</tr>
<tr>
<td>PV</td>
<td>45 g/kWh</td>
<td>[112]</td>
</tr>
<tr>
<td>Wind</td>
<td>10 g/kWh</td>
<td>[113]</td>
</tr>
<tr>
<td>WEC</td>
<td>8 g/kWh</td>
<td>[69]</td>
</tr>
<tr>
<td>Tidal</td>
<td>2 g/kWh</td>
<td>[69]</td>
</tr>
<tr>
<td>OTEC</td>
<td>23 g/kWh</td>
<td>[69]</td>
</tr>
</tbody>
</table>

### 6.2.2 Decision Variables

The decision variables of the optimization problem are the installed capacities of the storage and renewable energy technologies considered. Depending on the technology it can be obtained directly as installed capacity (biodiesel) or indirectly as amount of units installed. The 8 decision variables are then:

- \(X_{PV}\): Installed units of selected PV panel
- \(X_{W}\): Installed units of selected Wind turbine
- \(X_{T}\): Installed units of selected Tidal turbine
- \(X_{WEC}\): Installed units of selected WEC
- \(X_{OTECE}\): Installed units of defined OTEC plant
- \(X_{OTECSWAC}\): Installed units of OTEC-SWAC
- \(X_{Bat}\): Installed units of selected battery storage
6.2. Problem Formulation

$X_{Bio}$: Installed capacity of biodiesel generation [MW]

Assumptions

- Due to limitations in Matlab’s gamultiobj solver, the decision variables input are defined as floats (numbers with decimal point). This implies that fractional installed units can be calculated. However, despite the fact that in reality this is not possible, it is allowed as the purpose of the model is to estimate potential.

6.2.3 Constraints

The only constraints in the optimization problem are the bound constraints of the decision variables.

\[ lb_j \leq X_j \leq ub_j \quad \forall j = 1, \ldots, 7 \] (6.6)

Where $lb_j$ is 0 for all technologies except batteries where at least 1 battery has to be installed.

Upper bounds: For this model in theory, there are no upper bound because it is of interest to find the potential of each technology meaning that the amount of units installed can be as large as necessary as long as it is cost effective.

Nevertheless, for practical reasons the decision variables are constrained to limit the search space and reduce the computing time. The value of the $ub_j$ is determined for each island and each technology before the optimization is performed. This is done ranking by cost the available generating technologies for every hour. The least expensive technology is chosen and the amount of units needed to supply the demand is calculated. The maximum units needed for each technology throughout the year are used as the upper bounds for the optimization. This implies that for that hour when the maximum units occur only that technology is used to supply energy, which is the worst possible condition as it implies that no other technology is available (i.e. batteries and fossil fuel generation).

In reality, the amount of units that can be installed are largely constrained by factors such as land usage, social acceptability and environmental impact. However, as the objective is to estimate the overall potential of each technology this constraints are not taken into account.

6.2.4 Optimization method

The optimization problem described above is solved using Matlab’s gamultiobj solver. This routine is a modified NSGA-II algorithm which allows to solve multiobjective optimization problems. These algorithm has been used for HRES applications by [114, 115, 5]. The solver gamultiobj has various options to configure the algorithm, the settings used to solve the optimization problem are summarized in Table 6.2.
### Table 6.2: Main gamultiobj solver options

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PopulationSize</td>
<td>500</td>
<td>The number of solutions per iteration</td>
</tr>
<tr>
<td>MaxGenerations</td>
<td>150</td>
<td>Maximum number of generations the algorithm will run</td>
</tr>
<tr>
<td>ParetoFraction</td>
<td>0.6</td>
<td>The percentage of individuals from the population kept in the pareto front</td>
</tr>
<tr>
<td>CreationFcn</td>
<td>gacreationlinearfeasible</td>
<td>Creates a random initial population within the specified bounds</td>
</tr>
<tr>
<td>SelectionFcn</td>
<td>selectiontournament, 3 players</td>
<td>Selects the mating pool by doing a 3 player tournament</td>
</tr>
<tr>
<td>CrossoverFcn</td>
<td>crossoverintermediate, ratio = 1.4</td>
<td>The offspring is created in the same lines as the parents but offset a distance rand*ratio from parent 1. By making the ratio bigger than 1, the offspring is allowed to lie outside the hypercube formed by the parents.</td>
</tr>
<tr>
<td>CrossoverFraction</td>
<td>0.8</td>
<td>The amount of children generated by crossover</td>
</tr>
</tbody>
</table>

### 6.3 Cost Data

The cost data required for the optimization can be divided in two: the fuel costs which depend on the specific selected island, and the investment and O&M costs which are dependent on the technology but kept constant for all islands.

#### 6.3.1 Investment and Operation and Maintenance costs

The data used for estimating the investment and operation and maintenance costs is summarized in Table 6.3.
Table 6.3: Technology costs

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PV</td>
<td>1,375</td>
<td>0.76%</td>
<td>-</td>
<td>-</td>
<td>[116]</td>
</tr>
<tr>
<td>Wind</td>
<td>1,475</td>
<td>2.5%</td>
<td>-</td>
<td>-</td>
<td>[116]</td>
</tr>
<tr>
<td>Tidal</td>
<td>5,600</td>
<td>4.4%</td>
<td>-</td>
<td>-</td>
<td>[117]</td>
</tr>
<tr>
<td>WEC</td>
<td>5,900</td>
<td>3.8%</td>
<td>-</td>
<td>-</td>
<td>[117]</td>
</tr>
<tr>
<td>OTEC</td>
<td>10,000</td>
<td>3.7%</td>
<td>-</td>
<td>-</td>
<td>[117]</td>
</tr>
<tr>
<td>OTEC-SWAC</td>
<td>10,000 + 500(kWt)</td>
<td>3.7%</td>
<td>-</td>
<td>-</td>
<td>[117, 118]</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>650</td>
<td>2.3%</td>
<td>15</td>
<td>284</td>
<td>[116, 119]</td>
</tr>
<tr>
<td>Fossil Fuel generator</td>
<td>650</td>
<td>1%</td>
<td>6.5</td>
<td>Variable</td>
<td>[116]</td>
</tr>
</tbody>
</table>

The battery costs are shown in Table 6.4.

Table 6.4: Battery storage costs

<table>
<thead>
<tr>
<th>Battery</th>
<th>Unit price [USD]</th>
<th>USD/kW</th>
<th>USD/kWh</th>
<th>Cycles</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leadacid</td>
<td>9,888</td>
<td>1,977</td>
<td>686</td>
<td>2,800</td>
<td>[83]</td>
</tr>
<tr>
<td>Lion</td>
<td>8,333</td>
<td>1,666</td>
<td>1,515</td>
<td>3,000</td>
<td>[83]</td>
</tr>
<tr>
<td>Tesla Powerpack</td>
<td>96,700</td>
<td>1,934</td>
<td>460</td>
<td>3,000</td>
<td>[120]</td>
</tr>
<tr>
<td>Tesla Powerwall</td>
<td>5,500</td>
<td>948</td>
<td>407</td>
<td>3,000</td>
<td>[121]</td>
</tr>
</tbody>
</table>

Assumptions

- The costs for PV, wind and WEC are given as a range. The cost used for these technologies are the mean of the maximum and minimum values of the range.

- For tidal it was decided to use the maximum of the provided range due to the lack of pure tidal turbine projects as most of the projects are incorporated within a barrage.

- For the cost of OTEC-SWAC systems, the total cost of a SWAC plant is 1500 USD/kWt out of which 1000 is for cold seawater pipes. Nevertheless, the cost of the pipes is already included in the coupled OTEC cost, thus only the 500 extra cost of the SWAC plant is added. This is because in the proposed model, the cold seawater flow rate is always constant and that of the nominal capacity of the OTEC plant. Furthermore, the OTEC plant is designed to operate at 70% of its nominal capacity allowing the SWAC plant to operate at 100%.

- The cost for the biodiesel generators is assumed to be the same as that for diesel generators.

- The costs for extra fossil fuel generation is generation is considered to be that of the diesel reciprocating engines cost. This is because it is expected that any new installed capacity needed for the proposed scenarios would need to be able to respond fast to the load changes, making other generation technologies unfeasible.

- The biodiesel fuel price is assumed constant for all islands and is based on the price of Hawaii.
6.3.2 Fuel Costs

As explained in Chapter 5, the configuration of the conventional generation of each island is taken into account via the price of the fuel used for electricity generation. To do so, an average fuel price is calculated for each island and shown in Table 6.5. The average fuel cost is estimated by dividing the total fuel expenditure over the total electricity generation from fossil fuels. In the case where the total expenditure is not available, it is estimated by means of the island’s energy balance and prices for imported fuels.

Table 6.5: Averaged fuel prices for electricity generation.

<table>
<thead>
<tr>
<th>Island</th>
<th>Year</th>
<th>USD/MWh</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>2012</td>
<td>188.05</td>
<td>[122]</td>
</tr>
<tr>
<td>Cyprus</td>
<td>2015</td>
<td>69.92</td>
<td>[123]</td>
</tr>
<tr>
<td>Gran Canaria</td>
<td>2014</td>
<td>133.54</td>
<td>[124]</td>
</tr>
<tr>
<td>Mauritius</td>
<td>2015</td>
<td>65.71</td>
<td>[125, 126]</td>
</tr>
<tr>
<td>Oahu</td>
<td>2015</td>
<td>86.02</td>
<td>[127, 119]</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>2015</td>
<td>117.50</td>
<td>[128]</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>2014</td>
<td>256.56</td>
<td>[129]</td>
</tr>
<tr>
<td>Rhodes</td>
<td>2010</td>
<td>220.00</td>
<td>[5]</td>
</tr>
<tr>
<td>Shetland</td>
<td>2015</td>
<td>203.51</td>
<td>[56]</td>
</tr>
<tr>
<td>Streymoy</td>
<td>2015</td>
<td>103.02</td>
<td>[58]</td>
</tr>
<tr>
<td>Sumba</td>
<td>2010</td>
<td>221.45</td>
<td>[130, 131]</td>
</tr>
</tbody>
</table>
Chapter 7

Results

In order to address the research questions, 3 main cases and 5 scenarios were evaluated. Each case refers to a different situation which causes the electricity demand to vary, while each scenario refers to the technologies available to meet the demand. A summary of the results can be seen in Table 7.1

The three cases to be studied are:

1. **Base**: This case has the current electricity demand profile of each island.

2. **Heat electrification (H.E.)**: A 100% electrification of the domestic heat sector is considered for tropical islands.

3. **Cooling**: Cooling demand is taken into account, both current cooling demand and the expected maximum cooling demand.

Out of the multiple configurations calculated, two are highlighted for all the cases. The first one is the **cost-optimal** configuration which refers to the configuration with the minimum LCOS calculated and is shown as a star in the figures. The second one is the **equal price** configuration that is the configuration which results in the closest LCOS to the current electricity price in the island. It aims to be a measure of what could be possible if the population is willing to pay the same price as they are paying now for the electricity and is shown as a diamond in the figures. It is important to note as stated before, that the LCOS does not take into account costs associated with power distribution which may considerably modify the costs.
Table 7.1: Overview of cases and scenarios

<table>
<thead>
<tr>
<th>Case</th>
<th>Scenario</th>
<th>Islands</th>
<th>Technologies</th>
<th>H.E.</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base</td>
<td>PV &amp; Wind</td>
<td>All</td>
<td>PV, Wind, Battery, CG</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Base</td>
<td>Ocean Technologies</td>
<td>All</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Base</td>
<td>Biodiesel</td>
<td>All</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC, Biodiesel</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H.E.</td>
<td>PV &amp; Wind</td>
<td>Tropical</td>
<td>PV, Wind, Battery, CG</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>H.E.</td>
<td>Ocean Technologies</td>
<td>Tropical</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>H.E.</td>
<td>Biodiesel</td>
<td>Tropical</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC, Biodiesel</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>Cooling</td>
<td>Biodiesel</td>
<td>Tropical</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC, Biodiesel</td>
<td>-</td>
<td>Normal</td>
</tr>
<tr>
<td>Cooling</td>
<td>OTEC-SWAC</td>
<td>Tropical</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC, OTEC-SWAC</td>
<td>-</td>
<td>Normal</td>
</tr>
<tr>
<td>Cooling</td>
<td>OTEC-SWAC without Biodiesel</td>
<td>Tropical</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC, OTEC-SWAC</td>
<td>-</td>
<td>Normal</td>
</tr>
<tr>
<td>Cooling</td>
<td>Biodiesel</td>
<td>Tropical</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC, Biodiesel</td>
<td>-</td>
<td>Max cooling</td>
</tr>
<tr>
<td>Cooling</td>
<td>OTEC-SWAC</td>
<td>Tropical</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC, Biodiesel, OTEC-SWAC</td>
<td>-</td>
<td>Max cooling</td>
</tr>
<tr>
<td>Cooling</td>
<td>OTEC-SWAC without Biodiesel</td>
<td>Tropical</td>
<td>PV &amp; Wind + WEC, Tidal, OTEC, OTEC-SWAC</td>
<td>-</td>
<td>Max cooling</td>
</tr>
</tbody>
</table>
7.1 Case 1: Base case

7.1.1 PV & Wind

The PV & Wind scenario of the base case shows a positive impact of renewable energy integration for most of the islands as it decreases their LCOS, which is in accordance with the findings of multiple studies. Most cost optimal configurations are in the range of 30% to 70% with LCOSs ranging from 0.08 to 0.21 USD/kWh as can be seen from Figure 7.1. The LCOS range and the renewable energy penetration is consistent to what was found in other studies [4, 5, 15, 8]. Nevertheless, the calculated LCOSs are lower than what predicted by Blechinger [7] (0.27-0.36 USD/kWh) mainly because he considers only diesel as conventional generation fuel while this model takes the conventional generation mix as well as their local prices into account, which are often lower than diesel prices solely.

![Figure 7.1: Levelized cost of system with increasing renewable energy penetration. (Base case, PV&Wind scenario)](image)

The highest penetration levels at the cost optimal configuration can be attained in the Northern islands (Shetland and Streymoy) and in Aruba and Gran Canaria. This is primarily due to their high wind potential. As can be seen from Figure 7.2, for all islands (except Sumba) wind is preferred over PV, the main reason being that even though the costs of PV are smaller, the capacity factor of wind energy is higher than that for PV. It is important to point out that Sumba’s equal-price configuration does not exist. This is because the current electricity price in the island is subsidized and well below the diesel price used for power generation.

The islands of Cyprus and Mauritius have a cost-optimal configuration composed only of conventional generation. This is due to the fact that they have access to cheap fossil fuels, in particular Mauritius that has coal fired power plants.
Nevertheless, it can be seen that generally for all islands the increase in the LCOS up until 50% is small and it grows exponentially afterwards caused by the need for expensive battery storage. (Figure 7.3) This fact allows to rise two important points. First, that PV and wind technologies, can only supply directly up to 60% of the energy demand. As a consequence, reaching higher penetration levels is constrained by the storage capacity installed and because of the overcapacity needed to charge the batteries, a high amount of energy is curtailed. Second, the optimal configuration for the islands with “flat” LCOS region between 0 and 50% integration can easily change with fluctuations in the cost of fossil fuels, meaning that a small increase in the cost of the fuels can change the cost optimal configuration from 0% renewable penetration to a value up to 50%.
7.1.2 Ocean technologies

The addition of ocean technologies benefit mainly tropical islands which have OTEC resource. Although the technology is expensive, it has a very high capacity factor providing stable base power throughout the year. Nevertheless, because of the high prices of ocean technologies, the cost-optimal configurations for every island except Rarotonga and Sumba remain the same. These islands due to their small power system greatly benefit from the decrease of installed battery storage, allowing them to shift their cost-optimal configuration to high renewable penetration. It is important to point out that the LCOS of the cost-optimal configurations remain well in the same range as for the PV & Wind scenario.

![Figure 7.4: Levelized cost of system with increasing renewable energy penetration. (Base case, Ocean Technologies scenario)](image)

Furthermore, the benefit of base power generation of OTEC can be seen in the amount of installed capacity of this technology in the equal-price configuration (Figure 7.5). The addition of OTEC decreases the storage requirements as well as the total curtailed energy at higher renewable penetration (Figures 7.6 and 7.7).

Finally, it it important to mention that neither WEC nor tidal technology were found to have an important role in the highlighted configurations. Nevertheless, when reaching high renewable penetration specially in northern islands, both technologies start to be installed. In the particular case of Shetland (where tidal current data was available), tidal turbines start to be installed at 90% renewable penetration.
Chapter 7. Results

Figure 7.5: Relative installed capacities for Ocean Technologies scenario.

(a) Cost optimal

(b) Equal price

Figure 7.6: Electricity generation per source for the equal price configuration, Ocean Technologies scenario.

(a) Cyprus

(b) Puerto Rico

Figure 7.7: System energy production and curtailed energy for Ocean Technologies scenario.

(c) Rarotonga

(d) Shetland
7.1.3 Biodiesel

From the PV & Wind scenario it is clear that when reaching high renewable energy integration, the LCOS increases rapidly. This is caused by the overcapacity needed to cover the demand. From the Ocean technologies scenario it was found that the base load provided by OTEC for tropical islands allow them to reach higher penetration levels with reasonable LCOSs.

The main effect of considering biodiesel as a generating technology, is that it allows all islands to reach high renewable integration while avoiding the overcapacity needed in the PV & Wind scenario. (Figure 7.8)

However, it does not not shift the cost-optimal configurations to higher renewable integration as biodiesel is more expensive than the conventional fossil fuel mix, but it does provide the flexibility needed to meet the load profile, decreasing the amount of curtailed energy and storage requirements (Figure 7.10). As a result, 7 of the 11 islands reach a 100% renewable penetration in the same-price configuration.

Additionally, when biodiesel is considered, there is no need for storage as biodiesel technologies can also provide stability services. As a consequence, no storage is present in the cost-optimal
configurations. Nevertheless, biodiesel as a generating technology have important shortcomings for islands as will be discussed in Chapter 9.

![Graphs showing system energy production and curtailed energy for Biodiesel scenario.](a) Cyprus (b) Puerto Rico (c) Rarotonga (d) Shetland)

**Figure 7.10:** System energy production and curtailed energy for Biodiesel scenario.

### 7.1.4 Comparison between scenarios

When comparing the cases it becomes clear that generally cost-optimal configurations remain the same between scenarios; only in some cases where OTEC is available and fuel prices are high does the cost-optimal configuration is shifted (Figure 7.11). Moreover, the presence of ocean technologies, specifically OTEC, allows to reach higher renewable penetration with moderate LCOS as can be seen from the shift in equal-price configurations.

When comparing the performance of equal-price configurations (high renewable energy integration), the benefits and limitations of each scenario become clear. A perfect example is Puerto Rico shown in Figure 7.12. When only PV and wind are available, the system has the lowest emissions but a vast amount of energy is curtailed as overcapacity needs to be installed to meet the demand and a great amount of storage is needed to supply electricity when no wind or sun is available. The result is that for the equal-price configuration diesel is still required. When ocean technologies are available, OTEC is able to supply a base load, greatly reducing the amount of PV and wind needed (Figures 7.13b and 7.13c). Nevertheless batteries are still required for moments where neither wind nor solar power is available and for grid services, however, in order to charge them, overcapacity of OTEC is installed (Figure 7.13d). If biodiesel is present, the curtailment of PV and wind generation is greatly reduced and overcapacity of OTEC is avoided. Battery storage is scarcely deployed as biodiesel can provide stability services and meet the remaining demand. However, this system has the highest CO₂ emissions (Figure 7.13a).
Figure 7.11: Levelized cost of system with increasing renewable energy penetration between scenarios.
Figure 7.12: Puerto Rico power system performance.
7.1 Case 1: Base case

Figure 7.13: Lifecycle CO$_2$(eq.) emissions and installed capacities for Puerto Rico.
7.2 Case 2: Heat electrification

As discussed before, in tropical islands most of the heat consumed in the residential sector is used for two main applications: water heating and cooking. In this case the 6 tropical islands were evaluated under the proposed scenarios to see the effect that electrification of this activities would have on the demand and on the optimal configurations.

Puerto Rico will be used as example to summarize the results.

7.2.1 Comparison between scenarios

The most obvious consequence of considering domestic heat electrification is the increase in the electricity demand. However, not only the total energy demand increases but the electricity profile is modified. As can be seen from Figure 7.14, the morning peak becomes very important, mostly due to showering, and the evening peak increases considerably as well. The increase in total electricity demand caused by heat electrification for Puerto Rico is 24.6%, nevertheless it is important to point out that there can be hourly increases up to 64% the original consumption.

![Figure 7.14: Electricity demands. (H.E. case)](image)

In terms of the LCOS, two main observations can be made. (Figure 7.15) The first one is the (slight) increase in the LCOS values between the Base case and the H.E. case for all scenarios. This is caused mainly by the increase in installed diesel capacity (as extra diesel generation is required) and the extra cost associated with it, as shown in Figure 7.17f. The second one is that independent of the case, the change in LCOS at increasing renewable energy integration follow the same trend for each scenario, with values very similar between them. This is relevant because it suggests that the levelized cost of system is only influenced by the technology availability and not by the size of the demand, nor the daily electricity profile.

Additionally, the relative installed capacities of the highlighted configurations of each scenario remain the same independent of the case as shown in Figure 7.16. This suggests that the increase caused by the heat electrification on electricity demand and modification of the demand profile
Case 2: Heat electrification

does not have a strong effect on the configuration only on the total installed capacity. Nevertheless, it is important to note that PV is slightly favored in the cost-optimal configurations of the H.E. case with an increase from 3% of the total installed capacity under the base case biodiesel scenario to 9% under the H.E. case biodiesel scenario (Figure 7.16). Another thing to note is that as new diesel capacity is required, the configuration that has an LCOE equal to the current electricity price for the H.E. case biodiesel scenario is close to 100%, thus requiring diesel capacity for supplying power for some peaks and primarily for spinning reserves.

It is clear from Figures 7.16 and 7.17 for the H.E. case more capacity needs to be installed, but when it is deployed depends on the scenario rather than the case. Nevertheless, it is relevant to mention that domestic heat electrification triggers the deployment of OTEC technology, as it is required at lower renewable penetration levels. This is caused because the additional electricity added by the heat electrification causes extra capacity of diesel to be installed, and it is this additional cost that allows OTEC to be installed earlier (Figures 7.17d and 7.17f).
Figure 7.17: Installed capacities for Puerto Rico (H.E. case)
7.3 Case 3: Cooling

In this case, the service sector cooling demands for the studied tropical islands were estimated using the procedure described in Chapter 3. The most important characteristics are summarized in Table 7.2. The cooling loads are determined by the amount of cooled space which is a function of the climate (saturation) and GDP (availability) and the total time cooling is required which depends on climate and comfort temperature. The Caribbean islands (Aruba and Puerto Rico) have the highest cooling degree days and thus, cooling is required throughout most of the year, followed by Sumba, Oahu, Rarotonga and finally Mauritius. Additionally, Sumba, Rarotonga and Mauritius have the highest potential cooling demand growth as their availability is the lowest due to their lower GDP.

Table 7.2: Cooling demand characteristics.

<table>
<thead>
<tr>
<th>Island</th>
<th>CDD</th>
<th>Availability</th>
<th>Saturation</th>
<th>Availability·Saturation</th>
<th>Cooling hours [% of year]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>3833</td>
<td>55</td>
<td>80</td>
<td>44.4</td>
<td>96</td>
</tr>
<tr>
<td>Mauritius</td>
<td>2111</td>
<td>30</td>
<td>73</td>
<td>21.5</td>
<td>35</td>
</tr>
<tr>
<td>Oahu</td>
<td>2608</td>
<td>98</td>
<td>75</td>
<td>74.1</td>
<td>52</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>3375</td>
<td>87</td>
<td>80</td>
<td>69.1</td>
<td>89</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>2358</td>
<td>12</td>
<td>74</td>
<td>9.0</td>
<td>44</td>
</tr>
<tr>
<td>Sumba</td>
<td>3273</td>
<td>2</td>
<td>79</td>
<td>1.4</td>
<td>72</td>
</tr>
</tbody>
</table>

As seen in the previous results, all of these islands have OTEC potential, which allows to study the case of a hybrid OTEC-SWAC unit which on one hand is able to supply electricity and on the other can supply the required cooling power.

OTECSWAC units have the possibility of modifying the electric profile in two ways. For the cooling scenario, which is the current state, OTEC-SWAC can generate electricity savings by supplying the current cooling demand (given by the the parameters shown in Table 7.2) (Figure 7.18a). For the maximum cooling scenario, additional to savings of current cooling loads, OTEC-SWAC deployment can avoid the increase in electricity demand by supplying the future cooling loads (Availability = 1). If OTEC-SWAC is not installed, the electricity demand increases as shown in Figure 7.18b. It is important to mention that the electricity demand under no circumstance can decrease by more than the electricity savings originated from the current cooling demand scenario.
Additionally, the OTEC-SWAC units are able to provide flexibility on the power output of the OTEC plants. That is, their output power can decrease up to 70% when cooling is needed and the SWAC plant is running at 100% capacity. The consequence of this, is fluctuations on the power output dictated by the cooling demand.

### 7.3.1 Comparison between scenarios

Two main groups of results were obtained as was expected regarding their current availability values. The islands with high values of availability do not see a difference between the normal cooling and maximum cooling scenarios, thus, their configurations remain the same and the differences can be explained by the technologies available.

However, for those islands with low availability values more interesting results are obtained. Because the islands have low availability, there is an important difference between the normal cooling and the maximum cooling scenarios regarding cooling (and electricity) demand. As can be seen from Figure 7.19 in general two main LCOE trends exist given by the availability of biodiesel as a generating technology. However, taking a closer look at the plots, the maximum cooling scenarios are below the normal cooling scenarios. For Rarotonga this is true for all the range of renewable energy integration and for Mauritius the maximum cooling scenario is slightly higher at low penetrations but lower at high integration levels. The slightly higher values at low penetrations can occur due to extra diesel capacity needed. The decrease in the LCOE is more interesting and will be discussed below using Rarotonga as example. (Figure 7.22)
When looking at the cost-optimal and equal price configurations for the different scenarios (Figure 7.22), the first thing to note is that OTEC-SWAC is only deployed in the normal cooling scenarios for both of the highlighted configurations. Additionally, it can be seen that for the max cooling scenarios there is proportionally more PV installed than in the normal cooling.

Interestingly, in the normal cooling scenarios OTEC-SWAC is used as expected as it can cover the cooling demand and reduce the electricity consumption. In fact, whenever OTEC-SWAC is installed, it covers 100% of the cooling demand as shown in Figure 7.22a. The reduction of electricity demand, decreases the diesel (and biodiesel) required, having a favorable result in the LCOS. For the scenario where biodiesel was not available, the result is an overcapacity of PV and OTEC (Figures 7.22b and 7.22e).

However, for the max cooling scenarios OTEC-SWAC is completely avoided. Instead, PV is benefited as shown in Figure 7.22b. This is because the cooling demand profile matches the curve of solar power and any possible electricity saving causes the demand curve to deviate from the solar power profile. As PV technology is cheaper than OTEC-SWAC and the resulting new profile (all extra cooling load supplied with electricity) matches better PV generation, a higher percentage of solar power is used resulting in less curtailed energy. Figure 7.21. As the LCOS of the power system is dependent on the “useful” energy relative to the energy demand (curtailed energy has a negative impact on the LCOS) but independent on the total value of the demand, decreasing
Chapter 7. Results

(a) Base

(b) Cooling OTEC-SWAC

(c) Max Cooling Biodiesel

Figure 7.21: Rarotonga power system performance. (Cooling case)

the electricity demand with OTEC-SWAC is less favorable than increasing the total demand in a way that PV power is better utilized.
7.3. Case 3: Cooling

Figure 7.22: Results for cooling case for Rarotonga.
Chapter 8

Sensitivity

A sensitivity analysis was carried to understand the effect that certain input parameters have on the resulting optimal configurations. Five different cases are studied summarized in Table 8.1.

Table 8.1: Overview of Sensitivity cases.

<table>
<thead>
<tr>
<th>Case</th>
<th>Scenario</th>
<th>Variable</th>
<th>Variations</th>
</tr>
</thead>
<tbody>
<tr>
<td>WACC</td>
<td>Cooling</td>
<td>WACC</td>
<td>0%, -50%, +50%</td>
</tr>
<tr>
<td>CO2</td>
<td>Cooling</td>
<td>Objective Function</td>
<td>LCOS-coverage, LCOS-CO2, LCOS-coverage-CO2</td>
</tr>
<tr>
<td>Social acceptability</td>
<td>Cooling</td>
<td>Wind units</td>
<td>Wind, no Wind, Wind no Biodiesel, no Wind no Biodiesel, only Wind</td>
</tr>
<tr>
<td>Cost of Battery</td>
<td>Biodiesel</td>
<td>Capital and O&amp;M costs</td>
<td>0%, -12.5%, -25%, -37.5%, -50%, -62.5%, -70%</td>
</tr>
<tr>
<td>Cost of Ocean technologies</td>
<td>Biodiesel</td>
<td>Capital and O&amp;M costs</td>
<td>0%, -12.5%, -25%, -37.5%, -50%, -62.5%, -70%</td>
</tr>
<tr>
<td>Cost of OTEC-SWAC</td>
<td>Cooling</td>
<td>Capital and O&amp;M costs</td>
<td>0%, -12.5%, -25%, -37.5%, -50%, -62.5%, -70%</td>
</tr>
</tbody>
</table>

8.1 Weight averaged cost of capital (WACC)

The WACC is a discount rate used in energy project evaluation to take into account perceived risks and cost of opportunity. A high WACC reflects a higher risk, and thus allocates much more value to money in the present than in the future. When WACC is low, the risk is perceived as low and future cash flows will be considered more important than in the previous case. In the limit case where there is no risk and WACC is 0, the value of money in the present and future remains the same.

As can be seen from Figure 8.1, lower WACC values decrease the LCOE and favors renewable energy development, exemplified by the shift in cost-optimal configuration for the presented
case of Mauritius. It is important to mention that this same trend was found for Aruba and Rarotonga which were the other two cases studied.

Consequentially, the selection of WACC have an influence on the overall configuration of the energy system. When a high WACC is considered, the initial capital cost have a higher weight in the lifetime cost than the O&M cost and variable costs. As a result, expensive technologies are not favored even if they do not have any variable costs in the future. Considering a high WACC bring as a result more deployment of conventional generation and biodiesel, and as a consequence higher CO$_2$ emissions.

On the other hand, a low WACC make future costs important. As a result, renewable technologies (which often do not have variable costs) are favored over conventional generation and biodiesel. As a consequence, lower WACC leads to lower emissions, lower LCOE and earlier renewable energy adoption. The evolution of installed capacities and emissions with renewable energy integration for Mauritius is shown in Figure 8.2.

Figure 8.1: Levelized cost of system with increasing renewable energy penetration for Mauritius. (sensibility of WACC)
8.1. Weight averaged cost of capital (WACC)

**Figure 8.2**: Results for WACC sensibility, Mauritius.
8.2 Ocean technologies cost reduction

The reduction of cost for ocean technologies was considered simultaneous for WEC, tidal and OTEC. Ocean technologies have the potential to lower significantly the LCOE particularly in tropical islands where OTEC is available. (Figure 8.3) The results show that for Shetland where tidal turbines and WEC are feasible ocean technologies, only tidal becomes important and that happens with a cost reduction of 75%. As a result of the deployment of tidal, there is a reduction in the amount of wind installed.

![Figure 8.3: Levelized cost of system with increasing renewable energy penetration. (Ocean technologies cost reduction)](image)

For tropical islands, OTEC is definitely favored over WEC and tidal, thus, a reduction in the costs of the 3 technologies only lead to earlier adoption of OTEC. Using again Mauritius as example, reducing ocean technologies cost have multiple effects on the system’s configuration. Firstly, cost reduction of ocean technologies causes OTEC adoption to shift from 70% renewable integration (at 12.5% reduction) to 30% (50% reduction). Secondly, the capacity installed of PV and Wind is decreased while the need for battery storage is shifted and reduced. It is important to note that the reduction effect is higher on Wind than PV. Additionally the biodiesel requirements are delayed and reduced. A change in the optimal configurations can be seen with reductions as low as 12.5% at higher integration levels and further reduction leads to early adoption. A summary of the results are shown in Figure 8.4.
8.3 Battery storage cost reduction

Reducing the battery costs allows the LCOE to slightly decrease at high cost reduction (75%) as can be seen in Figure 8.5a. However, the most important effect can be seen in the optimal configurations at penetrations of 60% and higher. Reducing the storage cost benefit the deployment of PV generation as it allows to store the otherwise curtailed energy. This is particularly clear at higher penetration levels. As batteries are able to provide stability services, the use of biodiesel generation is delayed considerably. Finally, it allows to decrease the total CO₂ emissions and it limits wind energy deployment and favors PV implementation. This configuration shift start to become important at a cost reduction of 50%. Figure 8.5 summarizes the battery cost sensitivity results for Mauritius.
8.4 OTEC-SWAC cost reduction

OTEC is a promising technology but has yet to be implemented in large scale. Furthermore, SWAC has been successfully implemented throughout the world. [29] The implementation of OTEC-SWAC hybrid plants (or other hybrid combinations) can lead to more exposure for OTEC technology and enable its adoption. [17] As a consequence, cost reduction of OTEC-SWAC plants will cause a cost-reduction on OTEC technology. For this case, it is assumed that half of the cost reduction percentage of OTEC-SWAC is reduced in pure OTEC.

The results of the sensitivity analysis show that OTEC-SWAC plants can play a role with reductions of 25% in Aruba and 12.5% in Mauritius starting in both cases at 90% renewable integration.
and shifting to earlier adoption with higher cost reduction. The effect on LCOE is equivalent to what happens with ocean technologies cost reduction (Figure 8.6), nevertheless, there are interesting effects on the system’s configuration.

![Figure 8.6: Levelized cost of system with increasing renewable energy penetration. (OTEC-SWAC cost reduction)](image)

To address them, Mauritius is going to be used as example. As OTEC-SWAC has the capacity of decreasing the electricity profile, whenever the point is reached where OTEC-SWAC is favored there can be radical changes in configuration. In Figure 8.7 it can be seen that whenever the cooling coverage reaches 100%, there is automatically an abrupt decrease in the installed capacities of diesel, biodiesel, PV and Wind. Additionally, increasing cost reduction shifts the need for battery storage to higher renewable penetrations. Furthermore, as the OTEC-SWAC hybrid plant operates between 70%-100% OTEC capacity, more units installed mean that the cooling load is divided among more plants and therefore the OTEC unit can operate at higher capacities. As a consequence, and due to the fact that the decrease in OTEC-SWAC cost is greater than that of OTEC, OTEC-SWAC implementation is preferred over OTEC. It is important to note that a cost reduction of 25% allows OTEC-SWAC to be implemented at 60% renewable integration and decreases the installed capacities of Wind and PV from 700 MW to 300 MW and 250 MW respectively.
Chapter 8. Sensitivity

Figure 8.7: Results for OTEC-SWAC cost reduction, Mauritius.
8.5 CO₂ minimization

The objective functions are the most determinant factor of the final optimal configurations as they are used to choose one configuration over another during the optimization.

The coverage and CO₂ functions are correlated and as seen previously an increase in the renewable energy coverage leads to decrease in emissions. Nevertheless, the technologies favored by each objective function might differ and as a consequence, the optimal configurations. Additionally, the NSGA-II algorithm can cope with multiobjective optimization allowing to use the 3 objective functions simultaneously.

The results of this sensitivity case for Mauritius are shown in Figures 8.8a and 8.8b. The first thing to note is that the LCOE is virtually the same at lower penetration levels but at higher percentages the coverage objective function achieves lower values. This is because on the coverage function the cheapest technology is favored, independently of its CO₂ emissions. It can be seen that at high penetration levels for the scenarios considering CO₂ the LCOE increases exponentially, this is caused by an excessive deployment of battery storage which are assumed to be zero emission.

Moreover, when analyzing the equal-price configurations, the coverage function delivers a configuration with PV, wind and biodiesel which is the cheapest option, the CO₂ has the lowest amount of biodiesel installed and favors the deployment of OTEC and even WEC due to their low emission factors. Finally, the 3 objective functions give a different configuration which has OTEC-SWAC installed to help reduce the biodiesel used and thus, decrease its emissions however, it also has a vast amount of wind installed which is the most cost-effective technology for the island.
Chapter 8. Sensitivity

8.6 Social acceptance (wind turbine restriction)

The challenge for integrating renewable energy on islands goes beyond technical difficulties and economic constraints. Often it is the case, particularly for small islands, that their main economic activity is tourism. As a consequence, there can be low social acceptance of those technologies that modify the islands’ landscape, i.e. wind turbines. As seen before, wind is in most cases the most cost effective renewable technology, and the most important at low penetration levels. To study the effect of limiting wind implementation, the island of Aruba in the Caribbean will be used as example.

As expected, there is an important increase in the LCOE when wind cannot be implemented. Additionally, for the scenario where there is no wind available (OTEC-SWAC - no wind) the cost-optimal configuration is shifted from 68% to 82% of renewable energy integration but the resulting LCOE is higher from 0.1 \text{ USD/kWh} to 0.1721 \text{ USD/kWh}. This is because for Aruba the fuel cost is 0.188 \text{ USD/kWh}. Contrary to the case where only wind is considered, at high renewable integration the cost is limited by the use of biodiesel, whereas for the only wind case the cost increases exponentially proportional to the need for battery storage. (Figure 8.9) Additionally, it is important to mention that the equal price configurations occur at considerably different integration levels. As the electricity cost in Aruba is 0.25 \text{ USD/kWh}, for the OTEC-SWAC (both with wind and without) a 100% integration can be achieved at LCOE lower than the current electricity price. However, when only wind is considered, due to the high costs caused by the overcapacity and amount of storage required, the equal price configuration occurs at 91.8% renewable integration.

When looking at the optimal configurations, ocean technologies have a great boost when wind cannot be an option. OTEC and OTEC-SWAC are implemented since the cost-optimal configuration and OTEC’s capacity is increased at higher integration levels. Contrary to the OTEC-SWAC - wind scenario, in the OTEC-SWAC - no wind scenario the decrease in electricity demand caused by SWAC cooling is beneficial as it reduces the amount of diesel consumed, thus, being part of the cost-optimal configuration. Finally, it is important to point out that as a consequence of increasing OTEC installed capacity, PV capacity decreases with increasing penetration levels. The case results are shown in Figure 8.10.
8.6. Social acceptance (wind turbine restriction)

Figure 8.10: Results for social acceptance sensibility, Aruba.
Chapter 9

Discussion

9.1 LCOE and cost-optimal configurations

The cost-optimal configurations calculated in this thesis are consistent to what has been reported in other studies. Particularly, results are in range of what was found for the same island by Gioutsos and van Velzen. The difference in LCOE and coverage can be explained by differences in the cost values (i.e. PV, wind and fuel costs) and in specific with Gioutsos study on technology selection as he considered pumped hydro as an additional storage option. Nonetheless, the predicted cost optimal configurations are consistent for the same islands as can be seen from Table 9.1.

Additionally, when comparing the calculated values with Blechinger et al’s global assessment of renewable energy, the results differ more particular regarding LCOE (Table 9.2). In their study only small islands (1,000 - 100,000 inhabitants) were considered and a variable cost for diesel determined by the remoteness of the island was estimated. For this thesis, however, the fuel cost depend on the local technology mix and is often a combination of HFO, diesel and coal which result in considerably lower prices. Nonetheless, the cost-optimal coverage for Rarotonga and Aruba (which are within the population limits) are 50% and 69% which are comparable to the 49% of the Pacific Ocean and 64% of the Caribbean, respectively.

Table 9.1: LCOE and coverage values for selected islands.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>$0.099</td>
<td>69%</td>
<td>$0.11</td>
<td>75%</td>
<td>$0.105</td>
<td>63%</td>
</tr>
<tr>
<td>Gran Canaria</td>
<td>$0.089</td>
<td>60%</td>
<td>$0.09</td>
<td>65%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>$0.205</td>
<td>50%</td>
<td>$0.17</td>
<td>70%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rhodes</td>
<td>$0.173</td>
<td>52%</td>
<td>$0.17</td>
<td>54%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Shetland</td>
<td>$0.100</td>
<td>72%</td>
<td>-</td>
<td>-</td>
<td>$0.107</td>
<td>66%</td>
</tr>
<tr>
<td>Streymoy</td>
<td>$0.076</td>
<td>58%</td>
<td>$0.14</td>
<td>47%</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Sumba</td>
<td>$0.206</td>
<td>30%</td>
<td>$0.24</td>
<td>41%</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
9.2 The role of biodiesel

The possibility of biodiesel based generation as an alternative to conventional generation proved to be widely used throughout the different studied islands. Being a renewable energy source and a controllable one, it allows electricity systems to reach high renewable integration levels while avoiding high over capacities of other renewable technologies as PV and Wind. Additionally, due to the biodiesel’s ability to provide stability services, it reduces considerably the need for battery storage. Biodiesel was particularly important in non-tropical islands as neither base load generating technology nor cheaper storage technologies were available. Nevertheless, if cheaper storage as pump hydro is considered or base load capable technologies as geothermal are locally available, the trend might be different and closer to what was found for tropical islands. However, of the renewable energy sources considered it is by far the most important source of lifecycle CO₂ emissions, which goes against one of the reasons for transitioning to a clean system.

It is important to note that in this thesis the maximum capacity to be installed in each island was not limited in any sense as it was of interest to study the potential of the technology. However, in reality there are important constraints to the implementation of biodiesel based generation. The most important is land area restriction. Intrinsically, islands have very limited surface area. As shown by Gioutsos [4] PV and Wind deployment is not constrained by land area use. For the case of biodiesel it was found in this thesis that often over 1000% of island’s land area was required to supply the biodiesel required (information on the land use of biodiesel can be found in [94]). This could be potentially overcome if biodiesel could be sourced from algae. Nevertheless, more development is required for this technology to be implemented in large scale. [132] Therefore, it is likely that under the current circumstances, the same problems present with diesel will arise, namely higher prices for the biofuel and difficulties with logistics. For this thesis the price for biodiesel from Oahu was used for all the islands. Although the cost of biodiesel was always higher than that of fossil fuels for all the islands, it could be the case that the role of biodiesel was overestimated if higher costs exist for specific islands. Nonetheless, biodiesel can still have an important role when systems are nearing 100% renewable integration. Under this circumstance, the required capacity would be small (feasible for the location) and can help limit the amount of overcapacity and curtailed energy.

### Table 9.2: Average LCOE and coverage values per ocean. [7]

<table>
<thead>
<tr>
<th>Region</th>
<th>LCOE [USD/kWh]</th>
<th>Coverage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlantic &amp; Arctic</td>
<td>$0.338</td>
<td>55%</td>
</tr>
<tr>
<td>Caribbean</td>
<td>$0.279</td>
<td>64%</td>
</tr>
<tr>
<td>Indian Ocean</td>
<td>$0.353</td>
<td>40%</td>
</tr>
<tr>
<td>Mediterranean</td>
<td>$0.359</td>
<td>58%</td>
</tr>
<tr>
<td>Pacific Ocean</td>
<td>$0.359</td>
<td>49%</td>
</tr>
</tbody>
</table>
9.3 Ocean technologies possibilities

Ocean technologies are regarded as promising technologies able to harness the vast amount of energy stored in the ocean. However, from the results found in this thesis tidal turbines and WEC still have to develop to become relevant. Tidal turbines were only implemented in the island of Shetland at very high integration levels (>90%) and WEC was never selected as a significant player within the optimal configurations by the model under the studied cases. For the case of WEC, the Pelamis WEC was used as van Velzen showed that it had the highest ratio of production hours/no production hours and one of the highest capacity factors. For that reason and although other WECs can be used, it is not expected that WEC play a major role until the technology is improved or costs are abated. It is important to mention that lack of tidal current speed data did not allow to evaluate the potential of the technology on all the islands. Tidal currents are very location specific as the geographical features alter the current speeds, making it difficult to do a global assessment of the technology.

Ocean thermal energy conversion on the other hand, proved to be a important technology for tropical islands as it is able to produce constant base load electricity. It was found that OTEC implementation starts somewhere between 50% and 80% renewable integration for bigger islands, and are an essential part of the cost-optimal configurations for the smaller islands of Sumba and Rarotonga. Moreover, it was found that a cost decrease of 12.5% for Mauritius and 25% for Aruba was enough to make OTEC cost effective even against biodiesel being implemented at 70% and 80% of renewable integration. Further cost reduction leaded to earlier adoption.

9.4 The effect of domestic heat electrification

The electrification of domestic heat for tropical islands was modeled taking into account cooking and water heating as the main contributors for heat consumption. To create the resulting electricity profile, behavior information on cooking and showering were derived from the 2015 ATUS from which probability distributions were created. The resulting heat electricity demand had 3 peaks, with the most important being the caused by the morning and evening showers. From the energy use analysis performed in Chapter 3, it was expected that the increase in the electricity demand caused by the electrification of the domestic heat was in the range of 20%-40%. This proved to be the case for countries with high electricity consumption per capita such as Puerto Rico, Oahu and Aruba. However, the electricity demand increase by heat electrification in islands with lower electricity consumption and GDP was much higher. Thus, it can be the case that American standards and behaviors does not represent the reality of those places and lower electricity curves caused by heat electrification with slightly shifted peaks might occur.

Nevertheless, it is expected that the configurations would remain the same. It was found that the modification of the electricity demand caused by heat electrification does not have an influence on the optimal configurations, as the new electricity profile does not have a direct correlation with a specific renewable energy source. The consequence of having an overestimation of the heat demand is higher capacities needed but the configurations are expected to remain the same.

Finally, it is important to mention that although electrification can be a way to decarbonize the energy system, in the particular case of domestic hot water other renewable solutions exist. For instance, solar water heating has proven to be a reliable renewable technology which can greatly
Chapter 9. Discussion

decrease the energy required for low temperature water heating applications such as domestic hot water.

9.5 Service sector cooling demand and seawater air conditioning

Through the literature review it was found that there is currently not enough data regarding the specific cooling demands of the countries. In this thesis an energy balance approach was used to estimate the service sector cooling loads taking into account their population, climatological conditions and GDP. From the modeling two main cooling load scenarios were created, one given by the availability defined by their current GDP and another which represent the maximum cooling load that the island can have if it reaches saturation.

As the implementation of OTEC-SWAC causes modifications in the electricity demand curve, its potential and effect on the configuration showed two different trends. For the normal cooling case, OTEC-SWAC was installed, showing most of its potential in small islands, particularly Rarotonga. As a result of OTEC-SWAC implementation, the total required diesel and biodiesel was reduced. For the maximum cooling case, OTEC-SWAC was rarely implemented. The high correlation between cooling power needed and solar power, made it more cost effective to allow the demand to increase with a profile that matched better solar power generation. As a consequence, even though more PV was installed, less energy was curtailed and the overall LCOE values were lower.

9.6 Conventional generation fuel cost

The conventional generation fuel cost is a very relevant parameter for this model because it is where the configuration of different fossil fuel generating technologies is considered. This is because the fuel costs are calculated as the total fuel expenditure over the total electricity generated from fossil fuels, hence, the price takes into account the relative installed capacity of each fossil fuel. As a result of considering the fuel costs in this way, there are important variations between the fuel costs of the different islands. Places using cheaper fuels as coal in Mauritius, will have comparatively lower fuel costs than places where only diesel is used as in Rarotonga. Moreover, fuel prices have a very important effect on the optimization as fossil fuel consumption is one of the variables to be minimized. Cheaper fossil fuel prices, generally imply more polluting sources as coal, making the case for renewable energy adoption harder as they offer the cheapest solution for electricity generation. As a result, places as Mauritius or Cyprus which have access to cheaper fuels, have often cost-optimal configurations in 0% renewable integration.

However, this also means that fluctuations on fossil fuels prices can affect the location of the cost-optimal configuration. For instance, an increase of $0.025/USD/kWh on the fuel cost for Mauritius, shifts the cost-optimal configuration from 0% to 20% renewable integration. It is clear that any modification of the costs considered in the model will have an effect on the optimization, however, bigger fluctuations on fuel prices happen, as can be seen with the oil prices in the last 20 years. Therefore, having the most accurate estimates possible and considering the effect of maximum prices expected is encouraged.
9.7 Research approach and methodology proposal

This thesis was performed following the research approach loosely described in the Introduction. However, neither the approach steps nor their sequence were as clear at the beginning as they were by the end of the project. In the literature of system sizing of HRES, the methodologies described are more focused on how to select and build a model and their conforming blocks rather than how to approach the selection of possible scenarios. Nevertheless, in other areas, namely policy analysis, there are frameworks that have been developed that allow to systematically create and analyze future scenarios. Specifically for energy systems, John Robinson proposed a methodology on energy backcasting which presents many similarities to the approach undertaken in this thesis. However, the goals and scope of backcasting differs from what was performed in this project. In backcasting, the idea is to envision (desirable) futures and, in Robinson’s words, to “work backwards from a particular future end-point to the present to determine what policy measures would be required to reach that future”. Hence, backcasting analysis attempts to develop a timeline of milestones required and is broader in nature as it often considers social, environmental, technical and economical aspects, whereas in this project the focus was to study the effect of different supply and demand conditions on the optimal configurations under current circumstances.

Additionally to the energy backcasting methodology, Robinson proposed a more general backcasting methodology which could be applied to other areas of human activities. Both methodologies consist on 6 points and can be seen below:

**Energy backcasting**\[133\]

1. Specify goals and constraints.
2. Describe current energy consumption and production.
3. Develop outline of future economy.
4. Undertake demand analysis.
5. Undertake supply analysis.
6. Determine implications of the analysis.

**Backcasting method**\[134\]

1. Determine objectives.
2. Specify goals, constraints and targets.
3. Describe present system.
4. Specify exogenous variables.
5. Undertake scenario analysis.
6. Undertake impact analysis.

Combining the experience of developing this thesis and the methodologies described above, a methodology for doing projects consisting on HRES sizing for determining cost optimal configurations combined with various scenarios of supply and demand is presented ahead:
1. Define objective of the project. Specify the scope of the study and the goals and boundaries.

2. Analyze current situation to identify possible scenarios. In this project this was performed on the demand side, but it could be for the supply side as well. Select the scenarios to be studied.

3. Define the general characteristics of the system’s model to be used: level of detail, complexity and elements to be included. This is done considering the different conditions of supply and demand selected. Identify ways to model the scenarios that are in line with the defined characteristics.

4. Select the case studies to be studied in the analysis. The chosen case studies have to be such that the goals and objective can be achieved.

5. Collect the data needed as input to the model according to the defined characteristics.

6. Develop the model. The different blocks regarding supply and demand are integrated and assumptions of the model should be stated.

7. Evaluate the case studies with the scenarios of interest.

8. Perform an analysis and discussion of the results. It is encouraged to do direct comparisons between the scenarios.

The proposed methodology have various points in common to that proposed by Robinson such as current situation analysis, demand and supply consideration and modeling. Nevertheless, there are important differences mainly on the scope and objectives of the analysis. While in backcasting it is of interest to analyze a desirable future scenario in various dimensions (economical, political, social, technological, legal, environmental, etc), in this project it was of interest to study the effect that different scenarios of supply and demand have on the optimal configuration of an insular energy system considering current circumstances, thus the most important aspect analyzed was the technical. However, the model developed in this thesis allows to simultaneously analyze different scenarios and provide insights on the differences that they have on the optimal configurations. Additionally, it allows to quantify the effect of those scenarios in terms of the LCOE, optimal configurations, coverage or renewables and CO₂ emissions. This is the main difference to what is reported in the optimal configuration sizing literature, as in those studies [7, 14, 8, 5, 4, 135, 12] ; the focus is on finding the most efficient and precise way of determining the optimal configurations (usually) for a given location considering current conditions, without evaluating the effect of non-mature technologies and of demand scenarios on the proposed system’s configuration.

### 9.7.1 Considering the future

When thinking about supporting islands in their transition to a sustainable energy system, it is impossible not to think about the future. Evaluating current situations and determining the optimal configurations, allows to gain knowledge on what is possible now. That is, considering current state of the technologies via their performance and cost and the current socio-economical situation indirectly with the necessary demand and socio-economic data. However, in order for the transition to occur, changes need to be done in much more levels than just the technological and economical, requiring collaboration of different expertise areas.
Frameworks and methodologies which evaluate future scenarios such as backcasting can provide relevant insights on which changes need to occur in order to get to that desired future. Within the research group, Yash Agarwala performed a quickscan backcasting (combining Robinson’s and Quist’s backcasting methodologies) for two Caribbean islands aiming for a 100% renewable energy transition. He evaluates 2 scenarios and purposes the changes needed for the transition to occur. In his work, as it is often done in backcasting, because the analysis is so far into the future (where there is great uncertainty), the technical considerations are usually based on general potentials and the specific effect on the demand as well as the relations between the supply side are not considered.

It is in this situations where the model developed in this thesis could be used to help in analysis regarding the future, specifically backcasting. As the model developed is general, it can be used for virtually any island considered. Additionally, it could be easily expanded to account for more technologies and/or more demand scenarios. The time resolution of hourly time steps, although limited for some applications, is enough to understand the relations and implications of certain technologies and demand patterns on the optimal configurations. Additionally, it provides the possibility to quantify the power system chosen in terms of LCOS, CO$_2$ emissions and coverage of renewables. In particular, whenever a desired scenario is studied, the resulting visions on electricity consumption modification, technology implementation, fossil fuels restrictions, costs, emissions reduction, among others can be input to the model. Then, the optimal configurations can be determined for that particular future and provide insight on the relations between the technology selected. As a result, a quick comparison between what is envisioned and what could be technically possible could be assessed, and discussion (and possible modification) of either the assumptions or the power system model can be considered. Finally, the model is a tool that can allow comparisons between different envisioned scenarios in terms of the optimal configurations and performance of the resulting power system.

9.8 Model discussion and uncertainties

Hourly resolution

The model used in this thesis allows to simulate optimal configurations for island energy systems which can provide useful information on the potential of the different technologies for a given location. However, if a real system is to be designed, sub-hourly phenomena need to be taken into account. Specifically in the evaluation of stability services, the dynamic behavior of the different technologies becomes important as start-up times and ramp-ups can have an effect on the final system configuration.

Conventional generation

In this thesis the conventional generation was treated as a technology able to supply the power required at any point in time. This was done under the assumption that currently, islands’ electricity systems have a generation mix that allows for that flexibility. This approach allowed to evaluate the potential of renewable energy technologies on any selected location. However, when considering particularly small island systems, this assumption becomes more important as typically less units are installed. As a consequence, the operational limitations of each one become more important and can have an effect on the system’s configuration.
Demand and meteorological data

The demand data used for this thesis was obtained for different years, from different sources and in some cases incomplete. In all the cases the final profile was only for a single year, which remained constant throughout the lifetime considered in the LCOE calculation. Nevertheless, the results obtained in the thesis suggest that an increase in the total consumption in the future won’t have a significant impact on the relative optimal configurations unless there is a radical change on the electricity consumption behavior which completely modifies the demand curve’s appearance. Additionally, the meteorological used was also synthesized for only one year which remained constant for the project duration. As a result, the effect that a “bad” year for any resource might have on the LCOE and optimal configurations is not clear. It could be interesting to perform the optimization with data for a longer period of time in which the risk associated with the uncertainty and variability of some renewable sources is taken into account.

Spatial and social restrictions

The model developed in this thesis is general enough to be used to perform a global assessment of renewable energy potential on islands. However, it can be complemented by being coupled with a geographical information system. The coupling will allow to use georreferenced data, such that local spatial and social information can be considered. For instance, it can help restrict the available area for a given technology in the case where pronounced slopes exist or if a specific area is a national park. As a consequence, more detailed configurations can be achieved.

NSGA-II parameters

The selection, crossover and mutation operators, population size, number of generation, among other parameters have an influence on the performance of the genetic algorithm. In particular, bigger populations allow to search the solution space more thoroughly improving the optimal configurations specially at higher renewable energy integration where there is more dispersion in the results. The downside, however, is a considerable increase in computation time.

Control strategy

In the model used in this thesis a merit order control strategy was used. In it, the preference is to use first the battery storage, then the biodiesel and finally the fossil fuel generation. As a consequence, battery is discharged fast and then fuels are used. The benefits of this control strategy is that battery storage is used often, the downside is that it does not help to minimize the installed capacity of fuel based generation. The implementation of other control strategies can be explored with the goal of optimizing the use of the battery, which in turn can help decrease the installed capacities of both conventional and biofuel generation.
9.8. Model discussion and uncertainties

**Technology selection**

For this thesis 8 technologies were considered: PV, wind, OTEC, WEC, tidal, battery storage, conventional generation and biodiesel. Nevertheless, there are considerably more technologies which could be incorporated and which could play different roles. Geothermal energy is an interesting option as it has the capability to supply baseload power, however, information on geothermal potential on islands can be difficult to find [4]. Fuel cells are another technology which is worth looking into as it can be coupled with open cycle OTEC, electrolyzers and hydrogen storage. It is a dispatchable renewable energy source that has the capability to store energy and could be implemented in virtually every island.
Chapter 10

Conclusions and Recommendations

10.1 Conclusions

This thesis has investigated the potential effect that different conditions on power supply and electricity demand have on the cost-optimal configurations of hybrid renewable energy systems of islands. This was done by studying the roles of various generating technologies (PV, Wind, Ocean technologies and biodiesel) on the supply side and scenarios regarding residential heat electrification and commercial cooling on the demand side. For this purpose, a general model was developed on which the proposed loads and the power system performance was evaluated. The system was optimized using multiobjective optimization with economic (LCOE) and renewable integration (coverage) objective functions by means of a non dominated sorting genetic algorithm (NSGA-II). Eleven islands spread throughout the world were used as case studies.

Integration of renewable energy on islands

Integrating renewable energy technologies on islands has proven to be beneficial. Not only it reduces its dependency to foreign countries and protects them from fossil fuel price volatility but it effectively reduces the electricity cost. Wind energy deployment is favored at low renewable shares (up to 50%) as often cost-optimal configurations have an important share of wind capacity installed. PV technology becomes relevant at penetration levels in the range of 20%-40%. PV and Wind by themselves allow to reach shares up to 70% renewable integration without much need for battery storage. To reach higher penetration levels great overcapacities of PV and Wind are required and also great capacities of storage raising the costs considerable. As a consequence, other complementary technologies proved to be relevant mainly OTEC for tropical islands and biodiesel for the rest of the islands.

Ocean technologies

Currently, ocean technologies can play a role aiding islands transition to a 100% renewable system particularly at higher integration levels. In particular for tropical islands, it was found that OTEC has the potential to play a major role starting from 50% of renewable share. It’s potential for supplying constant baseload power reduced the need for overcapacity of Wind and PV and the need for high storage capacities decreasing the amount of energy curtailed. Tidal technology on the other hand proved to be important for Shetland in the last 10% to reach a 100% renewable system. Nevertheless, it is important to note that lack of tidal current information made impossible to make a complete assessment of tidal current potential as information could
only be sorted for 3 of 11 islands. Finally, of the technologies considered, it was found that WEC is the technology that needs further improvement and cost reduction to become an relevant contributor to the power generation mix.

**Biodiesel as diesel substitute**

The possibility of having biodiesel as diesel substitute resulted in a considerable decrease of the levelized cost of electricity at high renewable shares for all islands, having a more important effect on non-tropical ones. Being a controllable source, it was often preferred as it decreases overcapacity of uncontrolled sources as PV and Wind and it has the possibility to provide stability services reducing the need for battery storage. Nonetheless it was found that it also raises the CO$_2$ emissions and that it might be impossible for islands to be autonomous in the required biodiesel production due to land constraints, resulting in a similar case to that of current fossil fuel supply. In this regards, it is important to point out that biodiesel production was considered land based and algae production was not taken into account as it is still in early stage of development. Finally, the results make evident the benefits that a renewable controllable source can have and allow to think that biodiesel can prove to have an important role in the last 10% on the transition to a 100% renewable system. Finally, it was discussed that improvement on the control logic of the power system can allow to reduce the total capacity and usage of biodiesel.

**Residential heat electrification**

The effect of the electrification of residential heat demand was estimated for tropical islands considering water heating and cooking the main contributors. It was found that residential heat electrification can increase the total electricity demand of an island somewhere between 25% and 60% but have no real effect on the relative optimal configuration of the power system (the capacity installed increases but not the shares of each technology). Heat demand is usually highest early in the morning and on the evening, as a result the new electricity profile does not have a direct correlation with any renewable energy generating profile and the optimal configurations are not fundamentally modified.

**Service sector cooling and OTEC-SWAC**

Cooling loads for the commercial sector of tropical islands were estimated using socioeconomic and climatological data. Additionally, seawater air conditioning was considered through a hybrid OTEC-SWAC plant. Two scenarios considering current cooling loads and maximum cooling loads were studied. The reduction on electricity demand caused by supplying cooling power with OTEC-SWAC was favored only under the current situation with the current cooling level as it enabled a decrease in fuel consumption. Nevertheless the installed capacity of OTEC-SWAC was small (usually not covering 100% of the cooling demand) and the relative optimal configurations remained unchanged. On the other hand, the results for maximum cooling show that the resulting demand profile, caused by the addition of extra cooling loads, favors PV integration over OTEC-SWAC deployment due to its high correlation with PV power generation, having a significant effect on the LCOE and optimal configurations.
10.2 Recommendations

This thesis has studied the influence that different conditions of supply and demand have in the cost-optimal configurations of hybrid renewable energy on islands. It was done by evaluating 11 case studies using a general model suitable for studying more locations. Naturally, there is follow up research to be done and some recommendations are given below.

1. In order to expand the analysis and generate enough data to generalize globally and find trend between islands in different regions and with different social structures and physical characteristics, the combination of the model proposed with the use of a geographical information system is encouraged. As discussed before, georreferenced data can allow to include local restrictions while being able to provide global information. Additionally, the generality of the model allows to evaluate locations with different conditions.

2. This thesis studied the effect of residential heat electrification and commercial cooling demands regarding electricity demand scenarios. However, to fully understand the effect that possible future scenarios might have on the optimal configurations other scenarios can be considered. It is of particular interest the role that significant electric vehicle deployment can have in the optimal generation mix, specifically if V2G services are considered.

3. Future projects regarding energy transition of islands will likely need to address future situations where methodologies such as backcasting could be relevant. As it was discussed previously, the flexibility of this model allows to be used to evaluate any envision future scenario as it has been shown that it can cope with modifications in either the supply and demand side. Additionally, if multiple scenarios are developed, the model can aid in the comparison between them and help understand the relations between the technologies selected and the performance of the power system in the envisioned future.

4. One of the limitations of the model developed in this thesis is the restricted time resolution it uses. Although sufficient to perform analysis of the potential of sustainable energy technologies, sub-hourly resolution is needed to determine the real technical feasibility. Thus, it is encouraged to develop a sub-hourly model to test the proposed optimal configurations and further investigate what are the effects of considering the system dynamics on the final generation mix.

5. The proposed control scheme follows a merit order for electricity dispatch. However, different control logics may influence the amount of fuel used as well as the capacity installed of various generating units. Thus, it could be interesting to further investigate the effect that different control schemes have on the optimal configurations.

6. The model developed uses as input the electricity demand curve and the meteorological conditions for a period of one year. This is then assumed to remain constant throughout the lifetime of the project for the LCOE calculation. Nevertheless, it is known that the climatological conditions are never equal two consecutive years. Thus, considering a longer period of time for the system evaluation considering the fluctuations on meteorological conditions can allow to include these uncertainties, reducing the risk associated with the randomness of the resources and providing more robust optimal configurations.

7. Ocean thermal energy conversion turned out to be a very promising technology with the potential to play an important role in the energy transition of tropical islands. However, the technology is still new and has yet to be implemented. This thesis studied the potential of OTEC-SWAC hybrid plants to provide cooling power for the service sector. However,
further research can be performed on this or other possible applications, such as freshwater production, that can help accelerate the development of the technology.
Appendix A

Selected islands’ hourly averaged data

![Figure A.1: Hourly averaged data for Aruba](image)
Appendix A. Selected islands’ hourly averaged data

Figure A.2: Hourly averaged data for Cyprus

Figure A.3: Hourly averaged data for Gran Canaria
Appendix A. Selected islands' hourly averaged data

<table>
<thead>
<tr>
<th>Mauritius</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance</td>
<td>Wave height</td>
</tr>
<tr>
<td>Temperature</td>
<td>Tidal current speed</td>
</tr>
<tr>
<td>Zero crossing period (Tz)</td>
<td></td>
</tr>
<tr>
<td>Surface ocean temperature</td>
<td>Demand</td>
</tr>
</tbody>
</table>

Figure A.4: Hourly averaged data for Mauritius

<table>
<thead>
<tr>
<th>Oahu</th>
<th>Wind speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irradiance</td>
<td>Wave height</td>
</tr>
<tr>
<td>Temperature</td>
<td>Tidal current speed</td>
</tr>
<tr>
<td>Zero crossing period (Tz)</td>
<td></td>
</tr>
<tr>
<td>Surface ocean temperature</td>
<td>Demand</td>
</tr>
</tbody>
</table>

Figure A.5: Hourly averaged data for Oahu
Appendix A. Selected islands’ hourly averaged data

Puerto Rico

Rarotonga

Figure A.6: Hourly averaged data for Puerto Rico

Figure A.7: Hourly averaged data for Rarotonga
Appendix A. Selected islands’ hourly averaged data

Figure A.8: Hourly averaged data for Rhodes

Figure A.9: Hourly averaged data for Shetland
Figure A.10: Hourly averaged data for Streymoy

Figure A.11: Hourly averaged data for Sumba
Appendix B

Cost-optimal LCOE and coverage for the 11 islands.

Table B.1: Cost optimal configuration LCOE and coverage of renewable energy.

<table>
<thead>
<tr>
<th>Island</th>
<th>PV and Wind LCOE [USD/kWh]</th>
<th>Coverage [%]</th>
<th>Ocean technologies LCOE [USD/kWh]</th>
<th>Coverage [%]</th>
<th>Biodiesel LCOE [USD/kWh]</th>
<th>Coverage [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aruba</td>
<td>$0.099</td>
<td>69%</td>
<td>$0.099</td>
<td>68%</td>
<td>$0.099</td>
<td>68%</td>
</tr>
<tr>
<td>Cyprus</td>
<td>$0.077</td>
<td>0%</td>
<td>$0.077</td>
<td>0%</td>
<td>$0.077</td>
<td>0%</td>
</tr>
<tr>
<td>Gran Canaria</td>
<td>$0.089</td>
<td>60%</td>
<td>$0.090</td>
<td>64%</td>
<td>$0.090</td>
<td>62%</td>
</tr>
<tr>
<td>Mauritius</td>
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<td>0%</td>
<td>$0.072</td>
<td>0%</td>
<td>$0.072</td>
<td>0%</td>
</tr>
<tr>
<td>Oahu</td>
<td>$0.087</td>
<td>34%</td>
<td>$0.088</td>
<td>34%</td>
<td>$0.088</td>
<td>34%</td>
</tr>
<tr>
<td>Puerto Rico</td>
<td>$0.122</td>
<td>26%</td>
<td>$0.123</td>
<td>26%</td>
<td>$0.123</td>
<td>24%</td>
</tr>
<tr>
<td>Rarotonga</td>
<td>$0.205</td>
<td>50%</td>
<td>$0.199</td>
<td>83%</td>
<td>$0.199</td>
<td>83%</td>
</tr>
<tr>
<td>Rhodes</td>
<td>$0.173</td>
<td>52%</td>
<td>$0.172</td>
<td>50%</td>
<td>$0.173</td>
<td>54%</td>
</tr>
<tr>
<td>Shetland</td>
<td>$0.100</td>
<td>72%</td>
<td>$0.101</td>
<td>73%</td>
<td>$0.100</td>
<td>71%</td>
</tr>
<tr>
<td>Streymoy</td>
<td>$0.076</td>
<td>58%</td>
<td>$0.077</td>
<td>59%</td>
<td>$0.076</td>
<td>58%</td>
</tr>
<tr>
<td>Sumba</td>
<td>$0.206</td>
<td>30%</td>
<td>$0.156</td>
<td>88%</td>
<td>$0.156</td>
<td>88%</td>
</tr>
</tbody>
</table>
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