ENERGY AUTONOMY IN GREEK ISLANDS USING "ISLAND-SPECIFIC" RENEWABLE ENERGY TECHNOLOGIES.

Master of Science in Management of Technology

Graduation committee:
Prof. dr. K. (Kornelis) Blok
Prof. dr. ir. Z. (Zenlin) Roosenboom-Kwee

Faculty of Technology, Policy, and Management
Delft University of Technology

Athanasios Papoutsis
Student Number: 4744497

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Thesis report

By

Athanasios Papoutsis

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Chair & First Supervisor:	Prof. dr. K. (Kornelis) Blok
Second Supervisor:	Prof. dr. ir. Z. (Zenlin) Roosenboom-Kwee

Faculty of Technology, Policy, and Management • Delft University of Technology

Summary

This thesis addresses the urgent need for clean and sustainable energy systems on Greek Non-Interconnected Islands. Historically reliant on diesel and heavy fuel oil, these islands face environmental, financial, and energy security challenges. However, they possess abundant renewable energy resources, making them prime candidates for renewable energy integration.

The main research question guiding this study is to determine the cost-optimal configurations of hybrid renewable energy systems to achieve a substantial share of renewable energy penetration, specifically 60% or greater, on these islands. This research aims to offer actionable insights to policymakers, investors, and energy stakeholders, facilitating the transition to clean and affordable energy. To answer this question, state of the art modeling, and simulation tools (Homer Energy Pro) were employed. The study conducted a comprehensive analysis to identify optimal hybrid configurations for three different island categories, considering island-specific conditions, such as renewable resource availability, consumption patterns and type-size of wind turbines. Factors like solar, wind, geothermal and biomass resources, energy storage, and island size were incorporated into the simulations.

The research outcomes reveal that transitioning to predominantly renewable energy sources yield a remarkable reduction in electricity costs, promising substantial economic and environmental benefits. This becomes more noticeable in small islands category where the decrease in the cost of energy can reach up to 75%. Even in scenarios of full energy autonomy, the cost of energy remains lower than current levels, marking a promising path for energy transformation. The results for small islands showed, an average energy mix of 7 MW PV and 3 MW Wind Turbines is suggested to optimize the levelized cost of electricity. Medium-sized islands may benefit from 29 MW PV and 18 MW Wind Turbines, while large islands could consider a mix of 86 MW PV and 78 MW Wind Turbines. Solar power, in particular, benefits from the islands' high solar radiation, making it an optimal choice for smaller islands with consistent sun exposure. In contrast, larger islands with strong average winds tend to favor wind turbines. While biogas presents potential for electricity production, its implementation is limited, mainly on the larger islands. The research also examines the possibilities of geothermal resources, with a focus on the case of Milos, highlighting the broader potential of this renewable energy source. Importantly, the study underscores the critical role of energy storage systems, particularly batteries, in ensuring a stable and reliable energy supply. Investment requirements for achieving a 60% or greater share of RES on each island are a focal point of the analysis, varying significantly based on island size, energy consumption patterns, and the chosen RES mix. The range of investments varies from €6.5 million for the smaller island of Astypalaia to €605 million for Rhodes Island. These

investments primarily encompass the installation of renewable energy infrastructure, coupled with the development of energy storage systems. Diverse funding sources, including government incentives, international grants, public-private partnerships, and collaboration with energy companies, could be leveraged to support these necessary capital injections. These funding sources are necessary because attractive projects often come with substantial upfront costs and risks that energy companies may be hesitant to bear alone due to capital limitations, diversification strategies, and shorter-term investment horizons. Public and partnership funding help mitigate these challenges, share risks, and align with longer-term goals.

In conclusion, this research contributes significantly to the global challenge of transitioning to clean energy, by offering actionable insights into the cost-optimal integration of hybrid systems tailored for Greek Non-Interconnected Islands. Decision-makers can utilize these results to inform energy policy decisions, fostering sustainable development and energy independence for the islands. Policy recommendations include incentives for renewable energy adoption, smart grid development, and community engagement. Future research should explore untapped renewable sources, collect comprehensive data, investigate emerging storage solutions, and encompass all Greek islands for a more holistic energy transition strategy.

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Chapter 1 Introduction

1.1 Background

The climate change is a major challenge in the energy field. Seventy-five percent of global emissions are produced daily by the energy that powers our lives. In order to become energy carbon-neutral by the year 2050, a heroic commitment from our economies and societies is needed that goes well beyond simply setting long-range targets. To succeed in this transition, the International Energy Agency has published the first comprehensive road map for the entire global energy sector to reach net zero by 2050. (IEA, 2021)

The Paris Agreement recognizes that all the European islands are exposed to the climate change and the energy is depending on imports and fossil fuels. There are about 2400 islands in Europe that are small markets and isolated systems. Nevertheless, these islands are inhabited by 15 million European citizens and have the potential to become pioneers in the clean energy transition by adopting new technologies and implementing new innovative solutions. The European Commission is working to develop, explore and support the clean energy potential of islands of all of Europe. (European Commission, 2018)

The program of clean energy for Islands which is an initiative of the European Commission, aims to accelerate the transition to clean energy by helping islands to reduce their dependence on energy imports and make better use of the available local renewable energy sources. It will also promote modern and innovative energy systems, which can reduce greenhouse gas emissions of the islands. (European Commission, 2018)

The new EU Island Secretariat was set up to work with island communities. The first task of the Secretariat will be to gather and exchange best practices between EU islands and to provide technical assistance. Specifically, it will:

1. Promote the energy self-sufficiency of the islands.
2. Encourage the reduction of dependence on costly fossil fuel imports, reducing the pressure on public budgets.
3. Provide the best available, personalized solutions to enhance renewable energy sources on the islands.
   (European Commission, 2018)

In Greece, the guidelines of the European Commission for the period 2020-2050 are taken into account in policymaking. A series of key parameters are also considered (economic activity by industry, international fuel prices, CO_2 prices, lignite use level, etc.) in the selection of alternative scenarios for this issue. Three scenarios are studied to determine and evaluate alternative measures and policies to meet National and European objectives.

At the same time, the planning for the Greek islands, in addition to enhancing energy security and reducing their electricity costs, is an additional significant benefit from the electrical interconnections planned by IETO (Independent Electricity Transmission Operator), for the removal of "electrical isolation". The planning addresses the issue of installing in them a significant number of renewable energy units. Thus, according to the Preliminary Plan of the Ten-Year Development Plan 2022-2031, which was consulted by the Administrator (IETO), the interconnections of Crete, the Cyclades, and the Dodecanese, will create the technical conditions for the creation of new RES stations over 2 GW. (Δεληγιάννης, 2021)

According to the data from the conference held in 2019 in Croatia, two island cases have come into operation: Tilos, where a hybrid system (wind, photovoltaic, and battery) is already operating, which covers since last year the 80 per cent of the needs of the island and Ikaria, where Public Power Corporation (PPC) installed the "NAERAS" system, combining wind and hydroelectric energy. Ten additional islands (Sifnos, Kythira, Spetses, Kasos, Samos, Symi, Patmos, Amorgos, Zakynthos, and Crete) have joined at an initial or advanced stage in the initiative "Clean Energy for EU Islands "which supports the transition of island regions to lower carbon emissions. At the same time, the projects of CRES for the transformation of Ai Stratis into a "Green Island" are being implemented, as well as the project of Hellenic Electricity Distribution Network Operator (HEDNO) for the "Smart Islands" (Kastelorizo, Astypalaia, Symi). (iefimerida, 2019)(Notton et al., 2020)

The installation of hybrid systems in the non-interconnected islands, modeled on the internationally known and award-winning program "Tilos project" which operates on the island of Tilos and combines electricity generation from renewable sources, storage, and smart management of electricity, has been set as its first priority by the Ministry of Environment and Energy. The TILOS project was approved first among eighty competing projects under the European Horizon 2020 program. Tilos will become the first energy-autonomous island in Greece after securing European funding of 11 million euros for the creation of a hybrid wind and solar power plant. T (Notton et al., 2020) To date, the project has generated 3,300 MWh of clean energy, resulting in a reduction of 3,000 metric tons of CO_2 emissions. This equates to approximately 39,000€ in emission cost savings and 510,000€ in fuel cost savings.(Eunice, 2020)

After a thorough examination of the local literature concerning Greece, the forthcoming paragraphs will broaden our perspective by incorporating insights and discoveries from the international literary landscape.

The paper of Gioutsos D., et al. (2016) describes the cost-optimal configurations of hybrid renewable energy systems in six islands case studies, using photovoltaics, wind power, and diesel generation with the addition of pumped hydro and batteries as storage. He found out that the Levelized Cost of Electricity (LCOE) decreased a lot with RES penetration above 40% and with the lowest value around 70%. After that, LCOE increased again making 100% autonomy almost impossible. The wind power played the most important role and pumped hydro was preferred over batteries in case of penetration above 70%. However, he mentions that in the future a decrease in battery price by more than 50% would make it a more favorable solution. Last but not least, he recommended investing in wind power for at least 20% and wait battery prices to be reduced for better decisions. (Gioutsos et al., 2018)

The paper by Blechinger P., et al. (2016) discusses the potential for renewable energy systems on small islands all over the world. The authors performed a detailed techno-economic assessment of the potential integration of solar and wind power, along with battery storage, into the power supply systems of small islands. The authors found that there is a large potential for renewable energy on these islands and that implementing these technologies could significantly reduce greenhouse gas emissions and fuel consumption, as well as provide cost savings. Finally, the authors provide policy recommendations for facilitating the implementation of renewable energy on small islands. (Blechinger et al., 2016)

The review paper by Meschede H., et al. (2022) highlights the importance of studying renewable energy systems on islands as a representation of global efforts toward energy transformation. The findings suggest that achieving 100% renewable energy is technically feasible and economically viable. Most studies focus on assessing specific technologies or designing scenarios for achieving 100% renewable energy in particular regions. However, research on several world regions, such as Madagascar, Caribbean islands, Taiwan, Papua New Guinea, Indonesia, and the Philippines, is limited or lacking. Common solutions for transitioning to 100% renewable energy on islands include PV panels, wind turbines, energy storage technologies (such as batteries and pumped hydro storage), and biomass. The sustainability of biomass as an energy source requires careful analysis. Hydrogen and synthetic fuels are also considered for balancing energy systems, but their local production on islands comes with high costs. Importing renewable energy resources from the global market is an option for small islands. Sector coupling, particularly integrating power and transport sectors through smart charging and vehicle-to-grid (V2G) technologies, is crucial for successful energy transitions. However, multi-sectoral approaches and detailed industry sector inclusion are still not common in studies on 100% renewable energy islands. Evaluations vary in terms of input parameters, time series, and evaluation criteria, with economic parameters being the most commonly addressed. Environmental and social aspects are sometimes considered for a comprehensive sustainability assessment. The limitations of island areas for renewable energy deployment need to be taken more seriously, potentially leading to offshore floating PV/Wind Turbines and energy interconnection studies. Power line interconnections and material exchanges, such as biomass and waste, are explored for larger islands and archipelagos, but research on chemically bound imports like synthetic fuels is limited. (Meschede et al., 2022)

1.2 Problem Definition

The need for decoupling from conventional forms of energy as well as the growing measures of the European Union (EU) in this direction led to the promotion of Renewable Energy Sources (RES). More specifically, Greece, which can support any form of RES, especially hydroelectric, wind, and solar, has lagged behind compared to other EU countries in its implementation. There are several reasons why Greece has been slower to adopt renewable energy systems on its islands. One reason is that many of the islands have a high reliance on fossil fuels, which are often cheaper and more easily accessible than renewable energy sources. In addition, the infrastructure on many of the islands may not be well-suited to support the installation and maintenance of renewable energy systems. Additionally, there may be a lack of political will or financing to invest in renewable energy projects on the islands. Finally, there may be technical challenges related to integrating renewable energy systems into the existing energy grid on the islands. However, in recent years, the incentives provided by Greece and the EU for investments in electricity generation from RES are significant and great in number.

The problem of electrification of non-interconnected islands (Table 1) based primarily on the safety and reliability of the system is quite complex. Today, most of the islands are supplied by local production stations with conventional fuels mainly oil and its derivatives (fuel oil) with a much higher cost per MWh compared to the corresponding cost of the mainland system. The limited number of conventional production units, especially in the small non-interconnected islands, often makes it a great challenge to meet customers' demand for power and energy. A small fault in the transmission or production system, or even a scheduled disconnection of equipment for maintenance, can cause problems in the system, even its inability to meet the load requirement. Still, a more serious complication such as a natural disaster (intense winds, fires, or an earthquake, several possible scenarios in the Greek reality) can cause a blackout of the system. In this case, the system must have a black start capability to restart the units at the end of the disaster. The interconnection of the islands is still under study, but the interconnections of the islands are often quite difficult and expensive.

Table 1: Information of Non-Interconnected Islands with a population over 1000.

Island Name	Cluster	Area (km^2)	Population in 2011	Annual Energy from Conventional Thermal Units (MWh)	Peak Power Demand (MW)	Average energy cost 2021 (€/kWh)
Amorgos	Cyclades complex	121	1973	9032	3120	0.393
Astypalaia	Dodecanese complex	96	1334	6305	2310	0.465
Chios	Islands of East Aegean	843	51390	163070	44290	0.178
Ikaria	Islands of East Aegean	255	8370	24161	7450	0.450
Karpathos	Dodecanese complex	300	6139	32329	10890	0.240
Kythnos	Cyclades complex	99	1456	10711	3490	0.369
Lesvos	Islands of North Aegean	1636	86408	231349	66450	0.184
Limnos	Islands of North Aegean	476	16928	52731	13870	0.226
Milos	Cyclades complex	151	4839	41955	12420	0.253
Rhodes	Dodecanese complex	1401	115490	771517	209100	0.203
Samos	Islands of East Aegean	478	32977	136826	29050	0.209
Santorini	Cyclades complex	76	15097	167161	54230	0.165
Serifos	Cyclades complex	75	1420	8300	3660	0.330
Sifnos	Cyclades complex	74	2625	17709	6290	0.479
Skyros	Sporades Complex	207	2994	14890	4160	0.381
Symi	Dodecanese complex	58	2590	13969	4070	0.351

1.3 Research Objective & Approach

The research focuses on assessing the current state of the Greek Non-Interconnected Islands and exploring the potential for developing various forms of Renewable Energy Sources in these areas. Additionally, the research aims to investigate strategies and solutions to achieve a renewable energy share of 60% or higher in the Greek Non-Interconnected Islands. The 60% or higher renewable energy goal was determined through a literature review, revealing that surpassing this threshold leads to most cost-optimal energy solutions.

The approach to the issue is done with a modelling and simulation program that examines the environmental and economic development of the Greek non-interconnected islands that apply RES by investigating each of them with the direction of the energy independence. The primary goal of the thesis is, through the cost-optimal energy configuration to help most of the islands to increase the RES penetration by assessing the potential of renewable energy.

1.4 Research Contribution

As the energy crisis and global temperature increase, there is a pressing need for energy autonomy and sustainability. Besides, large Greek companies have already started talking about topics such as the transformation of Greek islands with the help of RES and batteries, while according to the literature, many implementations of RES projects are about to be completed in the near future. The dramatic increase in fuel prices and the rise of global temperature can be great opportunities for the transition of Greek islands. For this reason, it is important to investigate the cost-optimal hybrid RES, particularly in the case of non-interconnected islands of Greece that face the biggest problem and the opportunity for the development of RES is vast.

This research significantly advances the field of energy transition of the Greek Non-interconnected islands in several keyways. Firstly, this research encompasses an exhaustive analysis of all non-interconnected Greek islands, thoroughly scrutinizing each of the sixteen unique cases based on their individual characteristics. Moreover, this research strives to harmoniously integrate a blend of renewable energy sources, tailored to the specific resource availability on each island, incorporating solar, wind, and biogas in combination with battery storage systems. In addition, this research relies on the latest real-world input data for each renewable energy source (RES), eschewing synthetic data to ensure the development of more realistic and representative solutions. The precision of this input data is provided at an hourly level, further enhancing the accuracy of the analysis. Ultimately, this research encompasses a comprehensive exploration, taking into account all Greek non-interconnected islands and considering a spectrum of scenarios, ranging from 60% to 100% renewable energy penetration. This wide-ranging approach enables a thorough examination of the energy transition process and facilitates the discovery of optimal solutions.

1.5 Research Questions

This thesis tries to investigate the issues mentioned above in the problem statement section by incorporating them into a concept of a main research question that will this research hypothesis. The main research question is divided further into sub-questions that will help reduce the complexity of the prime research question and highlight the way this thesis should go into. A relative analysis for each of the sub-questions is selected that will be implemented capable of contributing to their answer.

Taking into consideration all the above, the main research question is developed as follows: <u>*What is the cost-optimal configuration of hybrid renewable energy system*</u>

in each Greek Non-Interconnected Island for achieving the 60+% share of RES and the transition towards clean and cheap energy?

The following four sub-questions shall aid in answering the main research question.

1. What is the current energy system in the Greek islands?
2. Which RES and storage systems are available and what is the potential in Greece?
3. What RES are suitable for each specific islands and what is the energy mix and capacity of batteries for each of them?
4. What are the investment requirements for achieving the 60+ percent share of RES in each island and where this investment should come from?

1.6 Methodology & Structure

The dissertation development methodology will be based mainly on modeling and simulation, bibliographic sources, published articles on the internet, excerpts, statistics, and reports of relevant RES research studies to investigate the development of RES in the Greek non-interconnected islands.

The first sub-question provides a review of the current situation in Greece and more specifically in the islands will be addressed alongside the existing strategic policy of the government for the development of RES and the electrification in the islands. The second sub-question addresses each technology of hybrid renewable energy systems and their potential in Greece, and it will be developed in a theoretical framework and sub-chapters.

In the second part of the thesis, the third and fourth sub-questions will be answered through the example of different case studies of Greek islands, the research will focus on highlighting the renewable energy source that has in abundance (in relation to the other RES) on each island. In addition to this specific RES technology, there will be a proposal for an energy mix according to the specific conditions in each island. A techno-economic model will be designed based on the energy mix and the use of batteries, to succeed in the 60+% share of RES and the transition towards energy autonomy in each island.

The techno-economic model will be based on the program HOMER Energy Pro and should be able to evaluate different scenarios of the different implementations of RES as well as diesel generators and battery storage. HOMER Energy Pro is a well-known and often-used simulation tool that can optimize the energy supply system of an island, which will contribute to finding the best configuration for each island. HOMER Pro has two options for optimizing a system. One is a grid search that tests all possible configurations within a defined range. The other is the optimizer, which uses a unique method to find the most cost-effective system. HOMER presents a list of configurations ranked by their net present cost, which allows you to compare and evaluate distinctive design options. Many alternative energy scenarios will be developed to incorporate RES and storage system, which will be compared with the existing system and its technological, financial, and environmental performance. The choice of this program was based on a comprehensive review titled "A review of 100% renewable energy scenarios on islands." The paper highlights that Homer stands out as one of the most widely utilized simulation tools in the literature, particularly in the context of small grid systems such as islands striving to achieve a 100% penetration of RES. (Meschede et al., 2022)

In the last part, the specific issues related to implementing Renewable Energy Sources (RES) on Greek islands will be identified and understood. Additionally, potential solutions aimed at overcoming these challenges and facilitating greater adoption of RES in this context will be explored.

Chapter 2 Literature Review of The Greek Energy Sector

In this section, it is described the main findings from the literature review of the papers, and it is divided into nine subsections. The first and the second subsection are presenting the historical background of the public power corporation and the interconnection of the islands with the mainland according to the literature. The third one is associated with a description of the current situation that exists in the Greek islands. The following five subsections are related to documents found in the literature about photovoltaic and wind power, biomass, and lastly energy storage. Eventually, a subsection with relatives' case studies about the autonomy of Greek islands is presented.

2.1 Historical Background of the Public Power Corporation (PPC)

Since the middle of the 20th century, the economic development of each country has been linked to the ability of its energy system to provide reliable, easy, and economical energy to all its consumers and citizens regardless of how it is used. The production and distribution of electricity from the planet's natural resources is a major issue of the world's scientific community with the rate of their use becoming constantly increasing and much higher than the rate of their replacement.

Greece's first power plant opened in 1889 and provided electric lighting for Athens' center and the Royal Palace. This was ahead of international progress, as the first public electrical installation was in New York in 1882, followed by London and Berlin a few years later. Athens was a pioneer in electrical power despite challenging conditions. The expansion of electricity initially was rapid in several cities of both continental and island Greece. The technology of the power plants until the year 1920 used steam engines that operated with imported coal and later oil engines prevailed and after 1950 it was exploited by exploiting water resources. (Αγτζίδη, 2014)

Post-WWII, Greece prioritized economic growth through ample and affordable electricity, utilizing domestic resources. Law 1468/1950 established the Public Power Corporation (PPC), a monopoly with autonomy in administration and finance, to ensure electricity production and transmission met market demand.

In 1955 began the exploitation of the lignite deposits of Ptolemaida of Macedonia for the production of energy. To date, despite the trends of reduction of energy production from lignite deposits, PPC exploits a total of about 63 million tons of lignite on an annual basis, holding second place in the European Union and fifth place in Europe.

Since the mid-1990s, the European Union has been attempting to liberalize the electricity market in its Member States, with the aim of achieving a reliable, cheap, and least impact on the natural environment during its production and supply. This liberalization was gradually regulated by three European guidelines 1996/92EP (European Parliament), 2003/54EP, and 2009/72EP which were incorporated into Greek legislation.

PPC's monopoly on the production, transmission, distribution, and sale of electricity has been completely lifted since 2012 with the exception of the Non-Interconnected Islands (NIIs) where it has been partially lifted.

The electricity market is supervised by RAE (Regulatory Authority for Energy) which was established in 1999 with the aim of controlling pricing and other policies of the sector and the gradual liberalization of the energy market so that Greece is in line with the directives of the European Union on free competition and the abolition of monopoly markets.

2.2 The Interconnection of the Islands with the Mainland of Greece

While until 1965 there was a single interconnected electricity transmission system (IETS) for the whole of mainland Greece, island Greece was supplied with electricity from independent power plants from the combustion of oil. Shortly after 1960, based on the criteria of the technical feasibility and the most economical solution for the electrification of the islands for 25 years, the first islands of the Saronic Gulf (Hydra, Spetses) and the Sporades (Skiathos, Skopelos) were interconnected in (NETS).

In the 1980s, the Ionian islands of Corfu, Zakynthos, and Kefalonia were interconnected by submarine cable, and the technical possibility of connecting Crete from the Peloponnese was reviewed. At the same time, despite the efforts, the interconnection of the Cyclades could not be achieved. In the 2000s, the Regulatory Authority for Energy (RAE) in collaboration with the National Technical University of Athens (NTUA), utilizing technological progress, examined the direct interconnection of the Cyclades from Lavrio to Syros and extension to the other islands. The completion of the project was delayed until 2020.

Subsequent interconnection studies in the decades 2000-2020, of the same RAE & NTUA collaborations for the rest of the Cyclades islands, the interconnection of the Dodecanese with Crete and the islands of the North Aegean with Evia, highlighted marginal economic benefits and were reviewed by the services of the Hellenic Electricity Transmission System Operator (HETSO) and PPC.

The issue came up again in 2020. IPTO presented the new Ten-Year Development Plan 2021 - 2030 which was submitted for approval to RAE and plans the construction of high voltage networks for the interconnection of the island of Greece. The exploitation of the RES of the islands was included in the new plan, as their benefits will be multiple. Initially, the islands will be exempted from polluting oil power plants; in addition, consumers throughout the country will gradually be relieved of a large financial burden as the charges of the Public Utilities (PU).

The new plan, following suggestions from RAE, presents the following investments in Renewable Energy Sources.

- For the Cyclades, gradually with the completion of the interconnections, the conditions are created for the development of 332 MW green energy projects. In detail, 100 MW is estimated to be able to be deployed in Santorini, Folegandros, Milos, and Serifos.
- For the Dodecanese and the islands of the North-Eastern Aegean, with the implementation of their interconnection, the possibility is given for the development of power plants from renewable sources with a capacity of 1,030 MW. More specifically, 360MW in Samos, Chios, and Lesvos, 570 MW in Limnos, Kos, Rhodes, and Karpathos, and 100 MW in Skyros.

The interconnection projects of the Non-Interconnected Islands (NIIs) with NETS are a strategic objective of IETO of the Hellenic Transmission System Operator and constitute the most important part of the 10-year program, treating more than 80% of the investment costs, contributing greatly to the achievement of national energy and environmental objectives.

(Operator of the Hellenic Electricity Transmission System (ADMIE), 2020)

2.3 Existing Situation of Greek Islands

In order to understand better the topic, an overview of the Greek islands' autonomous electrical systems is presented by Nikolas Katsoulakos (2019). Greece has over 2500 islands that cover fifteen percent of the total area of the country, but only 165 of them are inhabited. About 1,3 million people inhabit these islands and are important for the Greek economy as some of the islands are extremely popular touristic destinations worldwide. Many of these islands (around 61) are a big distance from the mainland and are defined as Non-Interconnected Islands (NII) because of 4 main characteristics: 1) These islands have various areas and populations and many of them are not easily reachable, especially from the sea. 2) They have huge access to renewable energy sources, especially from wind and solar. 3) They cannot connect with other electrical systems and this situation affects the reliability and energy security supply. 4) Because of the previous, there are problems concerning the stability of the network and the intermittency of renewable energy sources (RES). (Katsoulakos, 2019)

According to the data, ten percent of the total electricity consumption of the country consists of the energy consumption of the Non-Interconnected Islands. The electricity consumption has its peak in August which is almost double from the lowest during the November period. Up until now, more than 80 percent of the electricity needed is produced from fossil fuels which not only have big costs for the environment but also the finance and country's energy dependency on fossil fuels imports. The average cost of electricity in NII is 2,5 times higher than the prices in the mainland while at the same time, the structure of autonomous electricity systems does not allow the exploitation of the solar and wind energy potential of the islands. (Katsoulakos, 2019) Additionally to the technical limitations of the network, the installation and operation licenses have a difficult and complex way to acquire. The lack of information and local interests is another difficulty that is possible to delay or even cancel the development of RES and more specifically wind parks. (N. D. Hatziargyriou et al., 2006)

Last but not least, the author mentions that although the literature on energy in Greek islands is good, an overall examination of the energy landscape in the Non-Interconnected Islands is missing from the literature. (Katsoulakos, 2019)

2.4 Findings on Solar Power

Photovoltaic (PV) is a mature technology that is highlighted by various types of applications worldwide and has been used as grid-connected power stations or as stand-alone power systems that give the opportunity to remote consumers with a different renewable energy solution. In more detail, photovoltaic-based systems are one of the most attractive solutions to expand the grid in cases where there is high availability of water and irradiance. (Kaldellis et al., 2011)

Among Europe, Greece has the most solar radiation available during the entire year. Due to this reason, the total number of solar thermal water heater collectors per total population of the country is one of the highest in European countries. Nonetheless, the total installation of photovoltaics is quite low compared to other countries in Europe. (Hatziargyriou N., et al., 2006) Moreover, the area of Greek islands distinguishes from high or medium-high solar irradiance and with annual numbers that range from 1500 kWh/m^2 to 1900 kWh/m^2. Having these high numbers, the potential to exploit all this available solar energy can provide all the energy that local societies demand while having the least environmental and macroeconomic cost. (Kaldellis et al., 2009)

2.5 Findings on Wind Power

Nowadays, wind energy is also a mature technology and can be taken seriously as a crucial factor to reduce CO_2 emissions and protect the environment. At first glance, the development of wind farms needs to take place in windy areas to maximize the production of renewable energy sources. However, the capacity of the supply system to absorb wind energy depends on several factors: electricity demand, type and characteristics of conventional power plants, transmission capacity and availability of interconnections with neighboring networks, the time distribution of wind energy, operating rules of the system power supply, use and reliability of wind forecast models and others. (Caralis et al., 2010b) (Caralis et al., 2010a)

Greece has one of the best wind potentials in Europe, as the average local winds at the height of wind turbines can exceed 8-11 m/s during the summer, mainly in the coastal areas of mainland Greece and the Aegean islands, which are considered the most suitable areas for the installation of wind farms. The predominant winds in Greece are north, and more specifically during the winter, north, northeast, and northwest winds cover 45% of Greece. (Kotroni et al., 2014) However, a specific study for each Greek island is needed in order to determine the level of penetration of wind energy, which is different for every island, and will help to maximize the benefits for the electricity system. (Caralis & Zervos, 2007) In addition, wind generation should be limited sometimes when high wind and low load exist for network safety reasons and other generator limitations. There is a prevailing cutting rule from the public power corporation (PPC) that wind generation cannot exceed 30% of the hourly load demand. (Hatziargyriou N. et al., 2012)

Unfortunately, most of the wind farms have been concentrated in limited areas, such as the Peloponnese and Evia, because in these areas there is already an electricity network and the appropriate facilities required. (Kaldellis, 2005)

2.6 Findings on Biomass & Biogas

Apart from the classic renewable energy sources, Christopoulos O., et al. brings up in his paper the potential use of biomass energy in the energy autonomy of small islands. Biomass can be divided into 4 main categories: 1) Agricultural residues, 2) Solid municipal waste, 3) Energy crops, and 4) Wood chips. The energy needs, both heat and electricity, of a small island, can be met using biomass in two ways. The first one is direct combustion and the second is by using biochemical and thermochemical methods to produce gaseous, solid, and liquid biofuels. The use of biomass can help produce cheap energy and reduce the energy dependence on oil that is imported to the islands. Moreover, a new market of production of biofuels, heat, and electricity will be created that can stop immigration to urban areas by creating new jobs and bringing extra income to the local communities. The reduction of the quantity of waste should also be mentioned as the management of solid waste is a big problem for many islands that has not been solved. Lastly, forest biomass can solve another issue by maintaining firebreaks to prevent the spread of flames in a summer fire. On the other hand, crops are highly dependent on the regions and have many constraints so they cannot be found or grown in every island. There is also a limitation in the availability of animal waste for biogas production as they may be used in alternative ways. Although, all the drawbacks and the small scale and capacity of biomass in Greek islands, the author recommend the use of biomass as a big step towards the energy autonomy and sustainability of the islands. (Christopoulou et al., 2015)

2.7 Findings on Geothermal Power

The situation in Greece regarding the use of geothermal energy is favorable and sometimes ideal. So far it has been proven that there are high enthalpy geothermal sources on the islands of Milos and Nisyros, and geothermal sources of medium enthalpy in northern Greece and some Aegean islands. While there is a great need to reduce dependence on energy imports, our country continues to import to meet the energy needs of non-interconnected islands that have geothermal potential. (Παπαλέξης, 2021)

As far as low enthalpy reservoirs are concerned, which are at depths that are economically viable, smaller than 500 meters, there are many in Greece. It is estimated that their potential is approximately equal to 100 MW, only 9% of this is utilized, and from 2013 to 2016 no moves have been made to explore the potential. (Papachristou et al., 2019)

Finally, in Greece, no electricity is produced from geothermal sources, but there are prospects for the future in Milos and Nisyros, where there are high enthalpy reservoirs, as well as in Kimolos, Lesvos, Methana, and Akropotamos, which are areas with their geothermal potential under exploration, for the installation of 5-8 MW units for cogeneration of energy and heat. Geothermal sources are used only in thermal applications, such as balneotherapy sources, heating greenhouses, soil heating, settlement heating, and their use for the dehydration of agricultural products. (Koroneos & Fytikas, 1999)

2.8 Findings on Energy Storage

To store energy during high electricity production times, an energy storage system (ESS) is important to be able to return this energy when there is low solar irradiance, or at night or at low wind speeds. (Kaldellis J., et al., 2009) Storage technologies will increase and secure the introduction of renewable energy sources into autonomous insular grids. (Katsaprakakis et al., 2019) The size and the infrastructure of the islands are needed in order to select a certain energy storage system to minimize the fossil fuel contribution or even eliminate it. (Kaldellis et al., 2009) Adding to that, the maximization of renewable energy sources and the operation of the storage system at peak shaving or load shifting purposes should also be examined in the selection process. According to Katsaprakakis D., et al., the most frequently investigated ESS are:

1) **The pumped hydro storage system (PHS).** The PHS is one of the most mature and economically attractive technologies in electricity storage, with many of them installed and working all around the world. This system is optimum for demands higher than 5MW (medium and large systems). The lowest cost of PHS can be 30 €/kWh which is one of the best among any other storage technologies. Furthermore, PHS offers a high storage capacity, which can support the autonomous operation of an island for up to 19 days, helping the energy supply security enforcement. One of the biggest drawbacks of this technology is the high set-up cost despite the attractive economic indices. (Katsaprakakis et al., 2019) Additionally, the paper of Hatziargyriou N., et al., mentioned that the very dry environment that exists in many Greek islands is not recommended for exploiting hydropower. (N. D. Hatziargyriou et al., 2006) Despite these disadvantages, PHS can contribute with high-added value to the local social and economic community. Some examples can be the employment of local engineers, operators, etc. during the construction but also tourism and better management of energy and water resources. (Katsaprakakis et al., 2019)

2) **Compressed air energy storage system (CAES).** CAES systems are more optimum for small electricity systems with demands smaller than 1MW. The main drawback of this system is the thermal power disposal during the air compression phase, which is done using fossil fuels and reduces the storage cycle efficiency to 50%. Finally, this technology is still under development and characterized by high set-up costs and many technical difficulties. (Katsaprakakis et al., 2019)

3) **Electrochemical storage technologies, known as batteries.** Electrochemical storage technologies are also the most feasible option for small-size systems and offer a variety of alternative options with lead-acid batteries being the older and most economical while lithium-ion being the newest and most promising. In this case, the average storage cycle efficiency can range from 80 to 90 % but with a distinguished short life period (around 7 years) and the need for replacement. Compared to PHS, the autonomy operation period with batteries is much smaller (about 1 day) raising questions with the energy supply security enforcement. Another weakness of this storage technology is the excessive cost which can range from 400 €/kWh for lead-acid batteries up to 900 €/kWh for lithium-ion. (Katsaprakakis et al., 2019) At this point, we have to mention that although this paper is from 2019, the prices of the batteries have declined dramatically the recent years which makes this number not realistic and needs some further study and search.

2.9 Case Studies of Greek Islands

In this sub chapter, readers can anticipate a more thorough exploration of the subject as it delves into additional case studies that found in the literature. These case studies will provide a more comprehensive understanding of the concepts introduced in Chapter 1.1, offering valuable more real-world examples to illustrate.

In the paper "Overview of the Greek islands' autonomous electrical systems", the case of Astypalaia is investigated to improve the energy autonomous system of the island. The island of Astypalaia is far away from the mainland and other big islands, which makes it impossible to connect to a bigger grid for electrifying the island. Therefore, five scenarios are investigated using energy sources: photovoltaics and wind generators, and for storage: a small hydropower station and batteries. The results show a huge improvement of up to 45 percent renewable share and a 58 percent cut in fossil fuels consumption, with investments that cost does not exceed the number of 2,4 million euros. Although this paper has some limitations and focuses only on one island and without including the thermal energy in the simulations, it is a good example of how RES can penetrate the Greek islands and how similar implementation can happen to other remote islands. (Katsoulakos, 2019) A similar study was done for the island of Astypalaia from Konstantino Fiorentzi, with results achieving a maximum of 70% penetration of renewable energy sources and more than 60% reduction in fuel costs. Moreover, the battery energy storage system that was picked for the study could keep the system safe and stable during probable disturbances because of the fast response. (Fiorentzis et al., 2020)

The case study of Tilos is presented in the paper of Gilles Notton, et al. (2020), where the main goal is to maximize the renewable energy sources and supply electricity to the island while at the same time sustaining the electricity supply security. The implementation of a hybrid system with photovoltaic, wind, and batteries paired with a smart grid is described as targeting the partial autonomy of the island. The author mentions again the prohibitive cost of electricity alongside other problems like the numerous blackouts with a duration from 15 to 30 minutes. The system that was selected for this project consists of a wind turbine of 800kW, photovoltaic panels of 160kW, and battery storage with a capacity of 2.88 MWh. The outcome of this study shows some satisfactory results and the ability to reach a high level of autonomy because of renewable energy sources. It is also stated that similar projects can be implemented in other Greek islands or even over the world, by changing the size depending on the RES and energy needs of the location. (Notton et al., 2020)

Another island that is investigated in the literature by Skroufouta S. and Baltas E., (2021) is Karpathos. The island suffering to meet the energy and water demand like many other Greek islands. Up until now, the problem of water and irrigation is confronted with transporting water from other areas using watercraft, which is a high-cost solution and cannot be permanent. In this case, the solution that is studied, is a hybrid system of the existing production units, a combination of renewable energy sources, and a pumped storage hydroelectric system. This system was chosen specifically for this island due to topography and water availability. The specific study was focused to meet firstly the water needs and secondly, the energy needs, which is why only 30% of wind power and 20% of solar power goes to the grid and the remainder from RES goes to the desalination plant to secure the maximum water production. The result of the simulation showed 99% of met in water needs and an increase in energy autonomy of the island. Furthermore, the reduction of consumption of fossil fuels has multiple environmental benefits for the local place. Lastly, the author mentions that based on results and research work, some further research is needed to optimize the hybrid system because of the uncertain input data that were used. (Skroufouta & Baltas, 2021)

The last case that has been studied, is the one of project PHAROS. For the purpose of this project, an integrated software tool has been developed for a hybrid renewable system with the ability to search for the energy balance of autonomous islands. The project comes to solve the high electricity production cost that exists in the islands due to the small and outdated based power station. At the same time, trying to cut all the imports of clean water that are transferred to islands with costs that exceed 10€/m^3, using the abundance of solar and wind potential or even medium/high geothermal energy in some cases. Many simulations took place with different configurations and using many parameters (Photovoltaic power, wind power, charge and discharge rate of the energy storage, and capacity of the storage). As a concern the desalination, another algorithm was developed to cover the annual water needs. The result of this search shows the most cost-efficient solution for annual coverage through HRES to be near 85% with initial cost investment from 1,5 to 2 million Euro. On the other hand, if we want to have 100% autonomy, the investment should be triple compared to 85%. At the end of the paper, it also mentioned that a series of unfortunate political decisions have as a result an ineffective electricity system and water supply practices with negative effects on the local environment and the whole Greek economy. (Tzanes et al., 2017)

Chapter 3 Methodology and Data Parameters

3.1 Methodology

HOMER Pro is designed to achieve the lowest net present cost through its optimization process. The overall net present cost (NPC) of a system is the present value of all its costs incurred throughout its lifetime, minus the present value of its lifetime revenue. The system costs may include capital expenses, replacement costs, operating and maintenance expenses, fuel expenses, and emissions fines.

HOMER Pro determines the total NPC by summing the total discounted cash flows over each year of the project lifetime. This value serves as HOMER's primary economic output, which it uses to rank all system configurations in the optimization results. The simulated systems are sorted and filtered according to criteria defined by the user, allowing them to observe the best possible solutions. Moreover, it serves as the basis for calculating the total annualized cost [2] and **levelized cost of energy** (LCOE) [1].

$$\mathrm{COE} = \frac{C_{\mathrm{ann,tot}}}{E_{\mathrm{served}}} \quad [1]$$

$C_{\mathrm{ann,tot}}$ = total annualized cost of the system [€/yr]

E_{served} = total electrical load served [kWh/yr]

$$C_{\mathrm{ann,tot}} = \mathrm{CRF}(i, R_{\mathrm{proj}}) \cdot C_{\mathrm{NPC,tot}} \qquad [2]$$

$C_{\mathrm{NPC,tot}}$ = the total net present cost [€] The total net present cost (NPC) of a system is the present value of all the costs the system incurs over its lifetime, minus the present value of all the revenue it earns over its lifetime. Costs include capital costs, replacement costs, O&M costs, fuel costs, emissions penalties, and the costs of buying power from the grid. Revenues include salvage value and grid sales revenue.
i = the annual real discount rate [%]
R_{proj} = the project lifetime [yr]
CRF( ) = a function returning the capital recovery factor

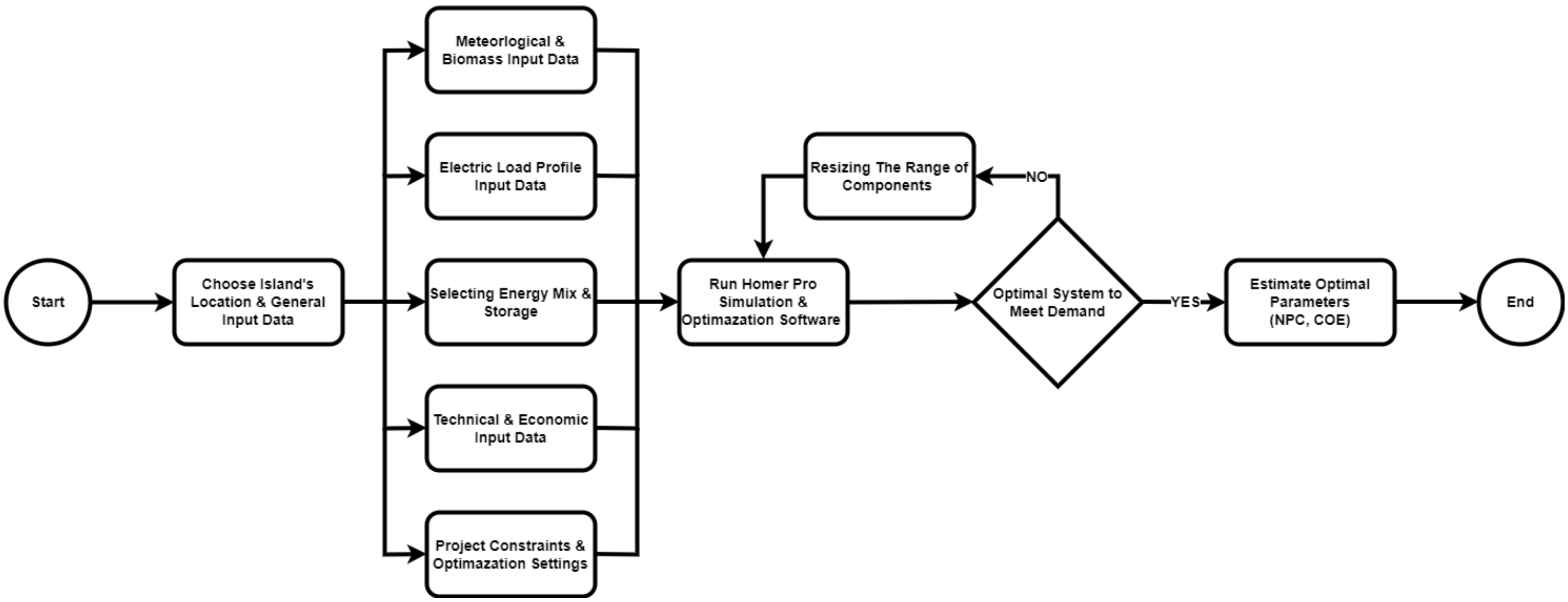
HOMER will make an attempt to simulate a viable system for all possible combinations of the equipment being considered. The number of systems that

HOMER simulates depends on how the problem is set up, and it can range from several hundred to even thousands.

HOMER performs simulations to model the functioning of a system by conducting energy balance calculations for each of the 8,760 hours in a year. It compares the electricity demand during each hour with the energy output that the system can provide at that time. In cases where the system includes batteries or fuel-powered generators, HOMER also determines how to operate the generators and whether to charge or discharge the batteries for each hour. If the system successfully meets the energy demands throughout the year, HOMER estimates the total cost of the system over its lifespan, taking into account various factors such as initial investment, replacements, operational and maintenance expenses, fuel costs, and interest charges. Detailed information on the hourly energy distribution across different components, as well as annual cost and performance summaries, can be accessed through HOMER.

The software offers four strategies for achieving this goal: Cycle Charging, Load Following, Combined Dispatch, and Predictive Dispatch. In the Cycle Charging strategy, generators operate at full capacity whenever they are needed, and excess power is used to charge the battery bank. This approach is best suited for systems that have minimal or no renewable power. On the other hand, the Load Following strategy involves generators producing just enough power to meet the current demand. This strategy is more suitable for systems that have abundant renewable power that may sometimes exceed the load requirements. The Combined Dispatch strategy aims to improve system performance by making more efficient use of the generator. This approach can outperform Cycle Charging and Load Following in some cases. Finally, the Predictive Dispatch strategy uses a dispatch algorithm that is aware of the upcoming electric and thermal demand, as well as the expected solar and wind resource availability. With a 48-hour foresight, it can operate the batteries in an economically efficient way, often resulting in lower system operating costs compared to other strategies available in HOMER Pro. This approach approximates modern systems that use forecasting to improve performance. (HOMER Pro Energy, 2021) All the four strategies were selected, and HOMER simulates and optimizes each strategy and presents the results based on the lower cost of energy.

Picture 1: Flowchart of the HOMER Pro optimization algorithm. (Thirunavukkarasu & Sawle, 2021)



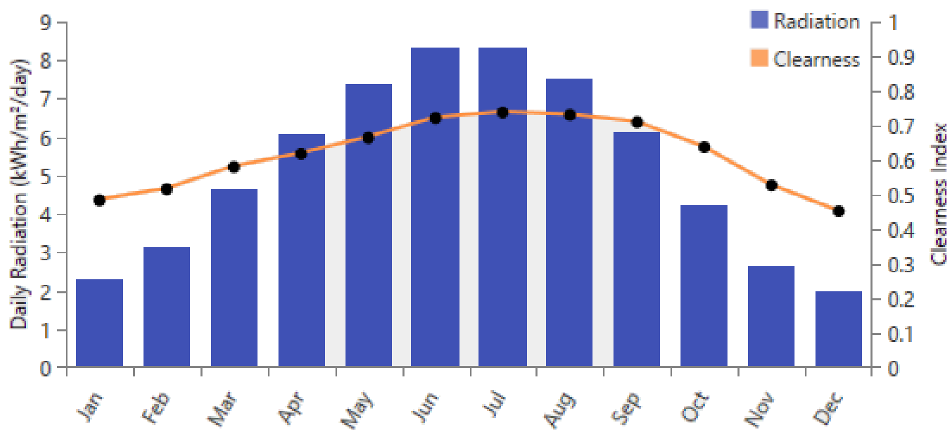
3.2 RES Resources Input Data

The Solar Irradiation and Temperature input data utilized in the HOMER Energy Pro program was extracted for each specific island's location from the Photovoltaic Geographical Information System (PVGIS) of the European Commission, which uses PVGIS-SARAH2database. (Pfeifroth et al., 2017) The hourly solar radiation and temperature data were downloaded for the year 2020. The location for measuring solar irradiation and installing PV systems was chosen manually, considering a high-altitude area with maximum sunlight exposure, minimal obstructions and were selected.

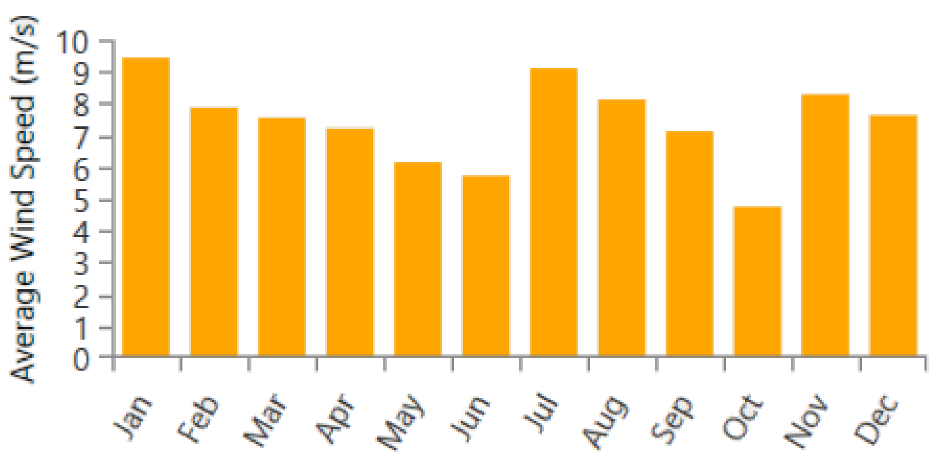
The Wind Speed data information was gathered for each specific island's location from NASA POWER Data Access Viewer which is based on Modern Era Retrospective-Analysis for Research and Applications (MERRA-2) data sets. (Gelaro et al., 2017) The hourly wind speed data were downloaded for the year 2020. The general method of the selection of the location points for retrieving wind speed data was primarily determined through a systematic approach. High altitude areas were manually identified as preferred locations due to their favorable characteristics, including sufficient available space and suitable conditions for wind turbine placement.

Moreover, the Biomass resource was added manually to the resources tab and was taken from the website of the Centre for Renewable Energy Sources and Saving (CRES). The biomass data were downloaded from the website of geospatial data and services for Greece ((CRES), 2015) and reflect the available solid waste in mass (tons), nonetheless, the data are not recently updated (2006) and they may deviate from the present.

Picture 2: Example of Monthly Average Solar Global Horizontal Irradiance (GHI) Input Data for the island of Amorgos.



Picture 3: Example of Monthly Average Wind Speed Input Data for the island of Amorgos.



Picture 4: Example of Average Temperature Input Data for the island of Amorgos

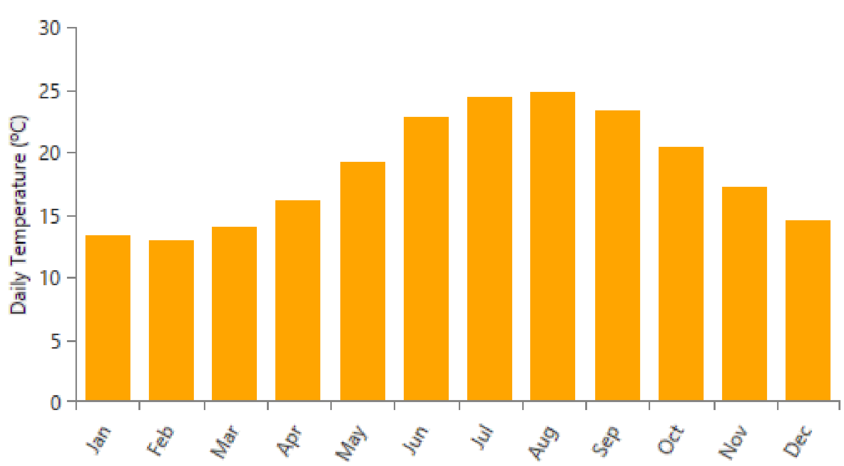


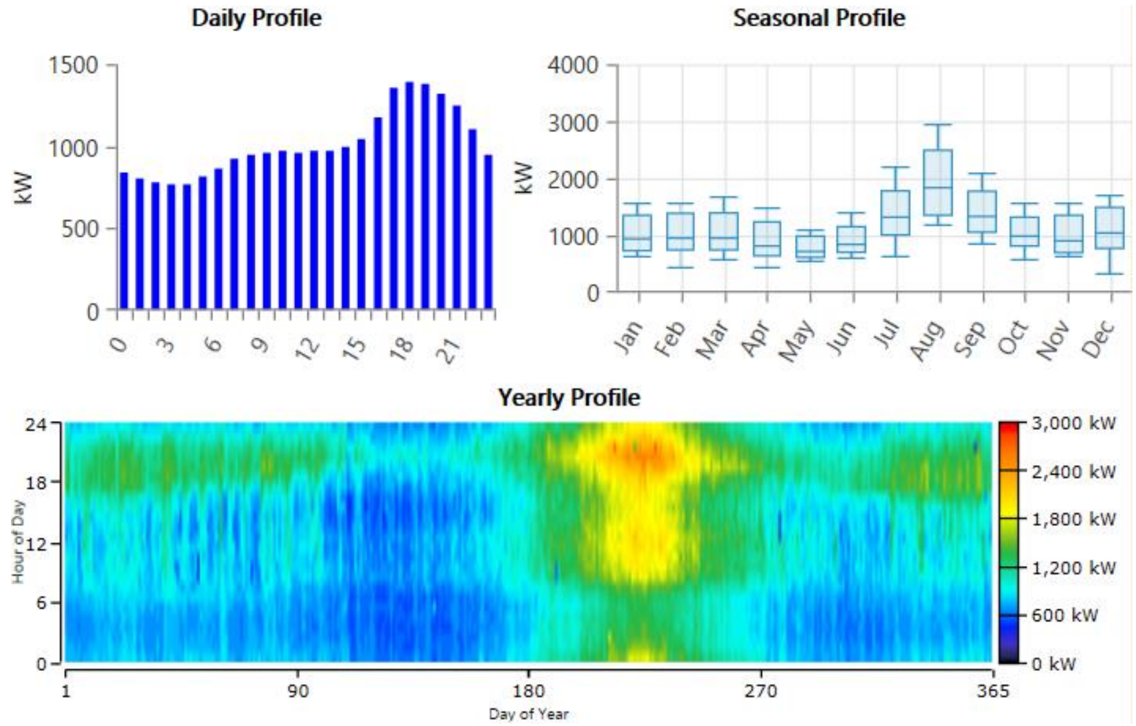
Table 2: Summary of Biomass resource input data for each island.

Island Name	Point sources of biomass (annual tons)	Arable crops (annual tons)	Greenhouses (annual tons)	Tree crops (annual tons)	Vineyards (annual tons)	Forests (annual tons)	Total tons of Biomass /Biogas
Amorgos	0	6	0	65	7	0	79
Astypalaia	0	18	2	31	9	0	60
Chios	3	138	36	2430	180	0	2786
Ikaria	1	55	7	1389	394	0	1846
Karpathos	1	47	2	208	63	0	321
Kythnos	0	21	0	88	53	0	162
Lesvos	2476	681	276	6532	540	1438	11944
Limnos	676	6018	29	800	1025	0	8549
Milos	1	503	52	1973	475	0	3004
Rhodes	213	2507	1800	5963	2924	0	13407
Samos	3057	270	100	3691	2774	0	9891
Santorini	0	80	1	37	800	0	918
Serifos	0	0	0	11	68	0	79
Sifnos	0	0	0	0	0	0	0
Skyros	0	98	0	20	54	3155	3327
Symi	0	0	2	16	12	0	29

3.3 Electric Load

The electric load is being set up through the hourly electric load data for the entire year. These data were taken from the Hellenic Electricity Distribution Network Operator (HEDNO S.A., 2023) The load data for each island were in the format of a table which contains the load consumption in MW for each hour for the entire year.

Picture 5: Example of Electric Load Input Data for the island of Amorgos.



3.4 Energy Mix & Storage

After determining the electric load, the power source for each island is selected by picking the desired energy mix and storage system.

3.4.1 Diesel and HFO Generators

The first step is to add the existing power source of every island, which is electrical generators. The Generic Large Genset (size-your-own) was selected to input and adjust the capacity in each case based on the total power that every island has. As capital cost the value of zero euros was used as the generators are already existing on each island. The Operation & Maintenance cost besides the diesel and HFO fuel price for every island were also taken from the Hellenic Electricity Distribution Network Operator (HEDNO S.A., 2023) and are different for each.

The table below summarizes the diesel generator input data for all the NIIs and contains the average fixed energy cost (€/h) from the year 2021 and the price for diesel fuel (€/l). The Average Total Energy Cost is the sum of the Average Variable Energy Cost (which mainly consists of the fuel price) plus the Average Fix Energy Cost (which consists of the operation and maintenance cost of the generators). In order to insert Average Fix Energy Cost into the program, a conversion needs to be done from €/MWh to €/h. This can be done by multiplying it by Annual Energy from

Conventional Thermal Units and then dividing it by the total annual hours (8760 h). A validation simulation conducted to compare the cost of energy generated by the simulation program with real-world costs, ensuring the accuracy of the program and verifying the generator input data.

Mazut is a heavy, low-grade fuel oil (HFO) that is commonly used in industrial applications, such as power generation and heating. Although the use of mazut has been regulated in many countries due to its high sulfur content and negative impact on the environment, some Greek islands that still use.

Table 3: Summary of average fixed energy cost and fuel prices on each island taken from the Hellenic Electricity Distribution Network Operator.

Island Name	Annual Energy from Conventional Thermal Units (MWh)	Average Fix Energy Cost 2021 (€/h)	Diesel Price (€/l)	HFO / Mazut Price (€/kg)
Amorgos	9032	189	0.775	
Astypalaia	6305	157	0.921	
Chios	163070	1917	0.718	0.398
Ikaria	24161	684	0.805	0.405
Karpathos	32329	383	0.945	0.389
Kythnos	10711	172	0.862	
Lesvos	231349	1428	0.839	0.406
Limnos	52731	578	0.676	0.383
Milos	41955	876	0.985	0.290
Rhodes	771517	6701	0.940	0.437
Samos	136826	1211	0.805	0.397
Santorini	167161	1317	0.854	0.280
Serifos	8300	135	0.700	
Sifnos	17709	448	0.857	
Skyros	14890	293	0.792	
Symi	13969	186	0.866	

3.4.2 Photovoltaics

The next step is to set up the renewable energy components that we want to add to our system. For solar power, the Generic flat plate PV was used in all cases as it is the most common type of use. The initial Capital Cost of PV was selected at 650,000 €/MW and the Operation & Maintenance Cost at 19,500 €/year per MW which is equivalent to 3% of the CAPEX. (The capital and O&M costs for the PV 650,000 €/MW and converters 300,000 €/MW equals to 950,000 €/MW which is the total installation cost of PV according to European Commission 2018)

3.4.3 Wind Turbine

The following phase is to add the wind power to the simulation model. For wind turbines, there were diverse types of turbines selected, depending on the population and the power demand of each island. For annual loads less than 40 GWh, the Leitwind-90 wind turbines were picked with the capacity of 1MW. While for other islands, medium wind turbines Leitwind-101 with 2MW capacity, and larger wind turbines Leitwind-101 with the capacity of 3MW for annual consumption above 150 GWh, were used. The Hub Height of the turbine was selected based on the manufacturer's recommendation. The initial Capital Cost of the Wind Turbine was selected at 1,450,000 €/MW and the Operation & Maintenance Cost at 43,500 €/year per MW which is equivalent to 3% of the CAPEX. (The capital and O&M costs for the Wind turbine were taken from European Commission 2018)

3.4.4 Storage

The next step is to include energy storage in the system to increase the penetration of renewable energy sources, help stabilize the electricity network and move each island into an autonomous energy system. For storage, Generic 1MWh Li-Ion batteries were as there is the most suitable solution for small islands and the price has dropped during the last years due to their development. The initial Capital Cost of Li-Ion Batteries was selected at 160,000 €/MWh and the Operation & Maintenance Cost at 3.200 €/year per MWh which is equivalent to 2% of the CAPEX.

The cost of PV, Batteries, and Inverters was selected based on a recent Business Plan of the company (ECOLOGICAL ENERGY S.A., 2022) concerns the operation of the 1 MW guaranteed power hybrid plant, consisting of a 2,000-kW photovoltaic plant and the control center and energy storage system through lithium-ion accumulators with a total storage capacity of 5.6 MWh in the island of Limnos. The cost of the investment amounts to a total of 2,400,000 EUR. According to the Bloomberg lithium-ion battery packs across all sectors have increased to 151 $/kWh in 2022 and will remain at this level for the year 2023 and will drop back again in 2024. (Henze, 2022)

3.4.5 Converter

In the end, a converter is needed to be added in the system to convert the AC into DC and the opposite. The generic System Converter was chosen for this purpose. The initial Capital Cost of the System Converter was selected at 300.000 €/MW and the Operation & Maintenance Cost at 9,000 €/year per MW which is equivalent to 3% of the CAPEX.

3.4.6 Biogas Generator

Last but not least, for some islands that have enough biomass to feed a biogas generator, the Generic Biogas Genset is selected with a capacity of 1500kW. The generic Biogas Genset was chosen for the islands that have enough biomass. The initial Capital Cost of Biogas Genset was selected at 3,400,000 €/MW and the Operation & Maintenance Cost at 115 €/h per MW. In biogas, OPEX figures include operation and maintenance costs, electricity consumption, technical support, insurance, transportation costs, and costs for the acquisition and handling of raw materials. The capital and O&M costs for the Biogas from anaerobic digestion ≤3MW were taken from (EUROPEAN COMMISSION, 2018)

3.5 Summary of Costs Input Data.

Technology	*Investment Cost*		*Maintenance and Operation Cost*		*OPEX (%CAPEX)*
PV	650,000	€/MW	19,500	€/MW-year	3%
Wind Turbine	1,450,000	€/MW	43,500	€/MW-year	3%
Geothermal	4,400,000	€/MW	132,000	€/MW-year	3%
Battery	160,000	€/MWh	3,200	€/MWh-year	2%
Converter	300,000	€/MW	9,000	€/MW-year	3%
Diesel-Genset	0	€/MW	1042*	€/hour	
Biogas	3,400,000	€/MW	115	€/hour	~20%

*The average fixed cost from all the islands. Every island has its unique fixed cost that represents the Maintenance and Operation Cost, that is implemented in the simulation.

3.6 General Input Data

For all the islands the Discount rate was set at 6.00% (Trading Economics, 2023), which is the default value from the program, the Inflation rate at 2.00%, and the Project lifetime at 20 years. The inflation rate was taken from Hellenic Statistical Authority (ELSTAT) based on the historical average data of the inflation rate of Greece for the last 10 years. (Kourtaki, 2023)

3.7 Analysis Constraints

The Maximum annual capacity shortage, defined as the fraction of total capacity shortage divided by the total annual electric load, was set to 0%. This value represents the highest permissible level of capacity shortage within the system.

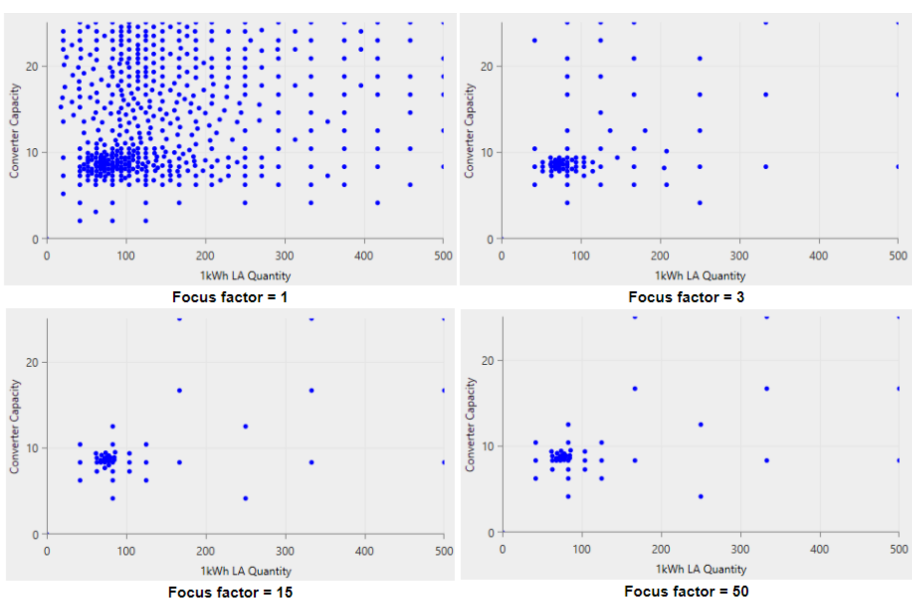
The Minimum renewable fraction refers to the lowest acceptable percentage of annual renewable energy generation. It signifies the threshold below which the contribution of renewable sources to the total energy mix cannot fall. This value was set to 60%.

As a percentage of load in each time step, HOMER includes a corresponding percentage of the primary load to the necessary operating reserve. The value of 20% means that the system must keep enough spare capacity operating to serve a sudden 20% increase in the load. Furthermore, HOMER incorporates a specific percentage of the annual peak load in each time step to determine the required operating reserve. This ensures a consistent level of operating reserve throughout the analysis. The setting for this value was adjusted to 20%. (HOMER Pro Energy, 2021)

3.8 Optimization Settings

The Focus factor setting determines the distribution of points in HOMER's optimization space, where each point represents a system configuration. A lower focus factor ensures more uniform coverage of the space, while a higher focus factor places points closer to existing point with a low NPC (Net Present Cost). Using a higher focus factor in optimization leads to faster convergence and requires fewer simulations overall, but there is a possibility of becoming trapped in a locally optimal solution. Although the default setting for the Focus factor is 50, which allows for quick and efficient generation of results, making it ideal for designing and iterating purposes. A lower value of 10 was used to increase assurance that the reported solution is the global optimum, even though it required more time. (HOMER Pro Energy, 2021)

Picture 6: Example of optimization space for 1, 3, 15, and 50 Focus factor values.



Chapter 4 Simulation Results

In this chapter are presented the outcomes of the simulation program that optimizes the best-case scenario for each of the islands using renewable energy sources and batteries. This chapter offers a comprehensive analysis of the data collected from the simulation, providing insight into the effectiveness of the RES and battery system in meeting the energy demands of the islands. The findings are presented in a clear and concise manner, utilizing various graphical representations to facilitate easy comprehension. Moreover, this chapter offers a glimpse into how the findings contribute to the existing literature and how they can be applied to real-world scenarios. Overall, the results presented in this chapter are significant, and they can serve as a foundation for further research in the field of renewable energy and island sustainability.

In order to process and virtualize better the results, the islands were categorized based on the annual electricity consumption and the three different size of wind turbines (1MW, 2MW, and 3MW). We classified the results into three categories: small (Category A), medium (Category B), and large islands (Category C). The islands in each category have similar annual electricity consumption and the same type of wind turbine. This classification system allows for a clear and concise understanding of the results, making it easier to compare and evaluate them.

4.1 Small Islands – Category A

In this category are the islands that have less than 40 GWh annual electricity consumption and the Leitwind-90 wind turbines of 1MW were picked for them. These islands are Amorgos, Astypalaia, Ikaria, Karpathos, Kythnos, Serifos, Sifnos, Skyros, and Symi. Furthermore, neither of these islands have enough biomass resources to support Biogas production so in none of them, Biogas Generators were used.

The simulation results presented in Figure 1 and Table 4 provide valuable insights into the cost-optimal configuration of hybrid renewable energy systems for each Greek Non-Interconnected Island. It is clear from Figure 1 that all islands have the lowest levelized cost of electricity (LCOE) between 85% and 99% penetration of renewables, with Karpathos having the lower penetration of renewables at 77% and Amorgos, Astypalaia and Ikaria having the higher at 94%. The trend for all islands is a decrease in LCOE until their lowest point, followed by a rapid increase after. The fluctuation effect that observed in the diagram occurs due to discrete number of wind turbines. Each discrete addition introduces a sudden decrease in the cost of energy, causing periodic jumps in the graph. This effect is more visible in smaller islands when a discrete change represents a considerable proportion of the total energy needs.

Table 4 presents the most optimized RES setup that succeeds in achieving the lowest LCOE for each island. The simulations show a distinct difference between the use of wind versus solar power, with the latter being used more in most cases. Amorgos, Astypalaia, Ikaria, Skyros and Serifos, for example, seem to rely more on solar panels as their main renewable source. Karpathos, on the other hand, has a balanced forty/sixty percent of Solar-Wind ratio. A logical explanation for the dominance of solar over wind, is the predictive output of photovoltaics compared to wind turbines due to the fluctuations and uncertainty of wind speeds that exist in these islands.

Comparing the current cost of electricity (data from 2021) from Table 1 with the results from the simulation in both Figure 1 and Table 4, it is remarkable that there is a vast decrease in the cost of electricity of up to around 75%. This decrease in cost is a significant advantage for the Non-Interconnected Islands as they currently heavily rely on imported fossil fuels for their energy needs. Moreover, it is clear from the graph that, in any case, the costs are lower than the current ones, even at 100% autonomy.

Figure 1:Levelized Cost of Electricity (LCOE) with increased Renewables Penetration above 60% for small islands.

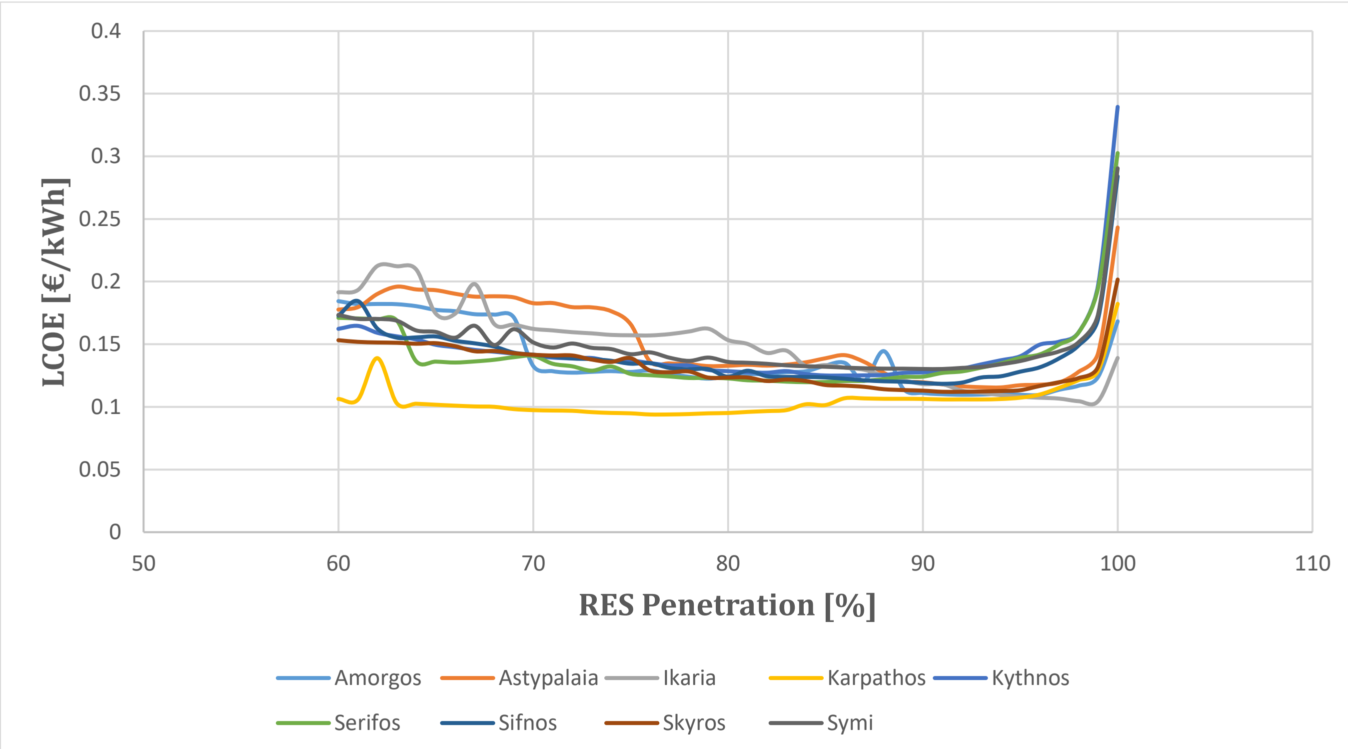


Table 4: Results for cost-optimal configurations of small island's energy supply systems.

A/A	Islands	PV (kW)	LTW 90 (1MW)	Existing System		Batteries 1MWh LI (#)	Strategy	NPC (M€)	LCOE (€/kWh)	CAPEX (M€)	Ren Frac (%)
				Diesel Gen (kW)	HFO / Mazut (kW)						
1	Amorgos	5358	1	4920		23	CD	14.2 M€	0.110 €	9.2 M€	96
2	Astypalaia	3562	1	4000		15	CD	10.9 M€	0.116 €	6.5 M€	94
3	Ikaria	15846	4	5000	9716	69	LF	45.9 M€	0.105 €	29.9 M€	99
4	Karpathos	4736	9	6600	10000	15	CC	49.7 M€	0.094 €	20.9 M€	77
5	Kythnos	4282	2	5200		19	CD	18.9 M€	0.125 €	9.3 M€	86
6	Serifos	3850	1	4900		16	CD	13.9 M€	0.120 €	7.0 M€	85
7	Sifnos	7924	5	9000		36	CD	33.8 M€	0.118 €	19.2 M€	92
8	Skyros	7671	2	6500		31	CD	23.6 M€	0.112 €	13.6 M€	92
9	Symi	7006	3	5000		25	PS	25.3 M€	0.130 €	14.1 M€	91

4.2 Medium Islands – Category B

The second category has islands that have annual electricity consumption of more than 40 GWh and less than 140 GWh and the Leitwind-101 wind turbines of 2 MW were picked for them. Three islands are in this category: Limnos, Milos, and Samos.

The simulation results for these medium-sized islands presented in Figure 2 and Table 5 exhibit similar trends to those observed for the first category. Limnos and Samos show similar graphs, while Milos has a lower graph. It's noteworthy that the optimal scenario of Limnos having one of the lowest percentages of renewable energy penetration (67%) compared to the other two islands in this group.

Additionally, Milos has a high enthalpy geothermal source of energy that can be utilized. Although the program used for the simulation does not include Geothermal Power as an option, it is likely that incorporating it would further reduce costs and increase the percentage of renewable energy sources. The findings as discussed in Chapter 2.7 suggest that there is potential for further exploration of Milos geothermal resource and its integration into the island's energy system to enhance its transition towards clean and sustainable energy.

The analysis of the optimal energy scenarios for this group of islands produced results that are similar to the findings of the previous group. Table 5 shows also the preference for solar energy compared to wind energy for the island of Samos because of the lower wind speed that blow to the island with wind capacity factor of 37%. Limnos has a closer to fifty-fifty percent the RES ratio while in Milos the high-capacity factor of wind is present. It is worth to mention that the optimal case of Samos (which is the 4th largest island in our case study), has the highest renewable energy penetration (80%) among all medium and large islands.

Figure 2: Levelized Cost of Electricity (LCOE) with increased Renewables Penetration above 60% for medium islands.

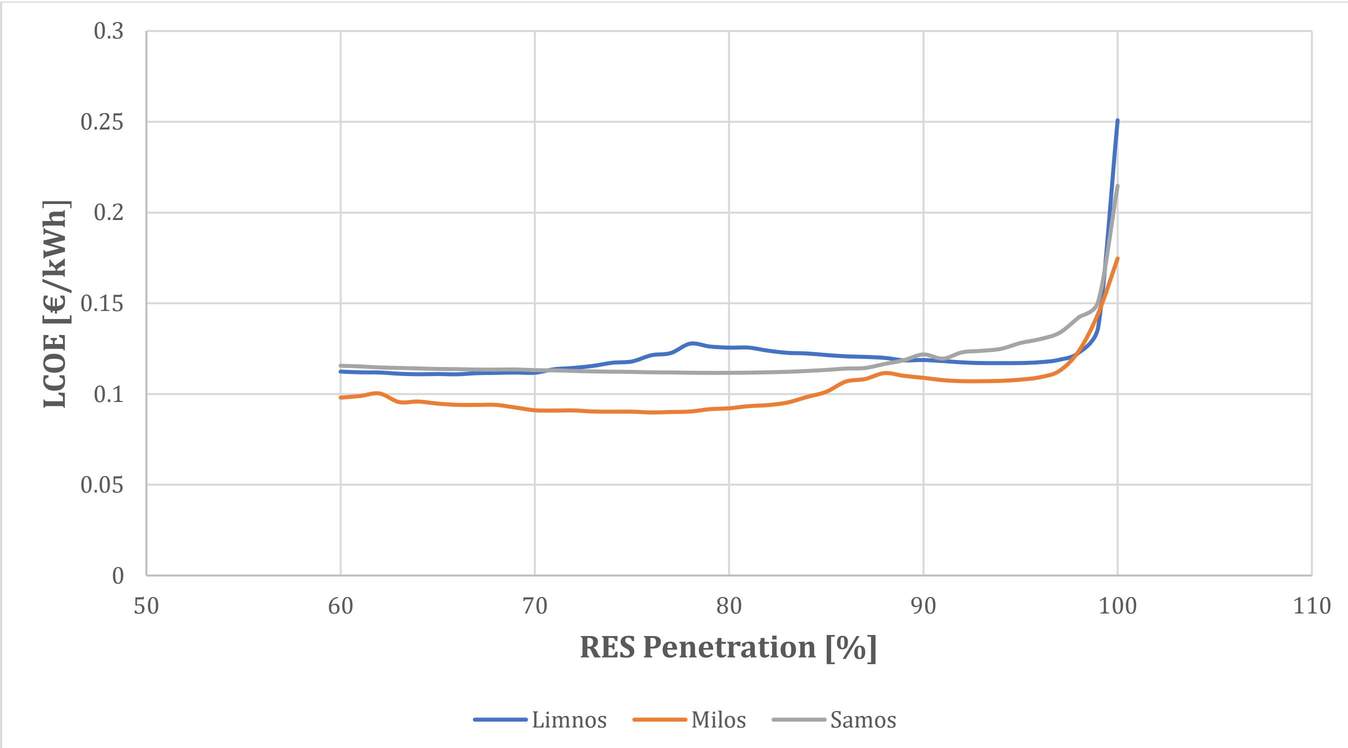


Table 5: Results for cost-optimal configurations of medium island's energy supply systems.

A/A	Islands	PV (kW)	LTW 101 (2MW)	Existing System		Batteries 1MWh LI (#)	Strategy	NPC (M€)	LCOE (€/kWh)	CAPEX (M€)	Ren Frac (%)
				Diesel Gen (kW)	HFO / Mazut (kW)						
1	Limnos	14120	5	3800	18000	40	CC	93.7 M€	0.111 €	34.9 M€	67
2	Milos	7730	8	4000	15000	24	CC	60.7 M€	0.090 €	24.8 M€	76
3	Samos	64627	14		47000	224	PS	256.2 M€	0.112 €	133.3 M€	80

4.3 Large Islands – Category C

The last category includes islands that have more than 140 GWh annual electricity consumption and make use of 3 MW Leitwind-101 wind turbines. The four last islands are Chios, Lesvos, Rhodes, and Santorini.

The trend observed in Figure 3 closely follows that of Figure 2, with the line initially remaining flat until around 99% renewable energy penetration before rising steeply to reach full autonomy. The lines for all islands are going parallel with Rhodes being at the top with the higher cost of energy and Chios at the bottom is similar order as the annual energy consumptions. Notably, the island of Santorini stands out as having the highest cost of energy (0.39 €/kWh) at full 100% renewable energy penetration compared to all other islands.

Table 6 presents the four optimized simulations with the lowest percentage of renewable energy penetration. These are the islands that have the lower cost of energy at the moment due to large scale of energy production and lower fuel costs that drop the total cost. The simulation of the island of Rhodes has the lowest capacity factor of wind speed (32%), which is an addition reason for the low rate of renewables. It is worth noting that Rhodes, along with Lesvos, are the only islands that include biogas as part of their optimized scenario, owing to their enough biomass resources. While 65 wind turbines may initially seem like a significant number for an island, it's important to consider that Rhodes is one of Greece's largest islands, spanning an expansive 1,401 square kilometers. Additionally, its two mountains offer ample space for accommodating these wind turbines as they are not habitable.

Figure 3: Levelized Cost of Electricity (LCOE) with increased Renewables Penetration above 60% for large islands.

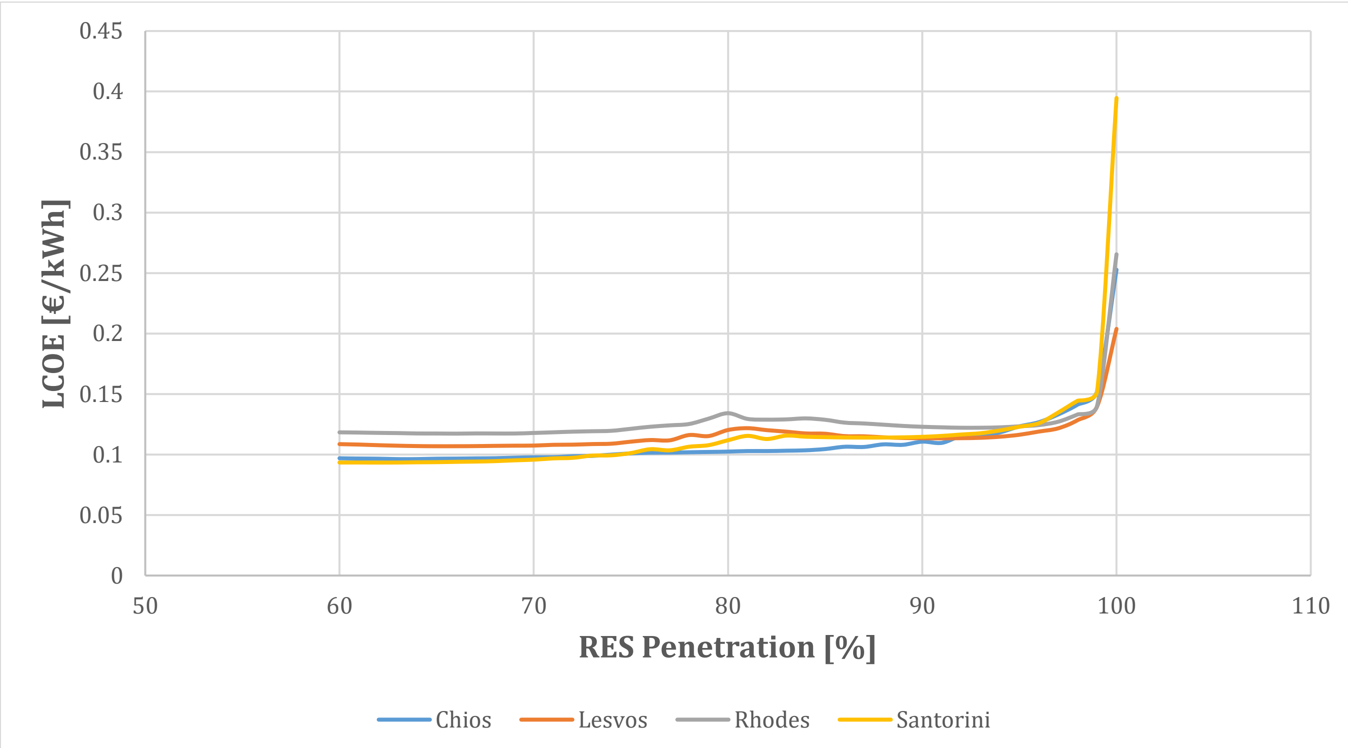


Table 6: Results for cost-optimal configurations of large island's energy supply systems.

A/A	Islands	PV (kW)	LTW 101 (3MW)	Existing System		Biogas (kW)	Batteries 1MWh LI (#)	Strategy	NPC (M€)	LCOE (€/kWh)	CAPEX (M€)	Ren Frac (%)
				Diesel Gen (kW)	HFO / Mazut (kW)							
1	Chios	35031	12		64452		64	CD	260.2 M€	0.096 €	97.3 M€	64
2	Lesvos	51590	17	31800	49500	1500	104	CC	412.7 M€	0.107 €	147.0 M€	65
3	Rhodes	231416	65	186000	119000	1500	555	CC	1449.2 M€	0.117 €	604.9 M€	67
4	Santorini	26770	10	37039	34878		66	CC	214.2 M€	0.093 €	85.0 M€	62

Chapter 5 Discussion

5.1 Comparison of Results with Literature Finding

In this chapter, we delve into a comprehensive comparative analysis between our own research outcomes and key findings from existing literature. In comparison to the existing literature, the results obtained in this study provide both confirmatory and dissimilarity insights into the phenomenon under investigation.

The article of Katsaprakakis et al., (2019) assesses optimal electricity storage solutions for Symi, Astypalaia, and Kastelorizo islands with RES integration. Two storage approaches are explored: seawater Pumped Hydro Storage (PHS) for larger islands and electrochemical storage using lead acid or lithium-ion batteries. Wind parks and photovoltaic stations are considered, aiming for 70%+ RES penetration at feasible costs. PHS is viable for Symi and Astypalaia; Kastelorizo needs wind-photovoltaic-battery setup. PHS proves competitive for Symi and Astypalaia due to favorable land, while Kastelorizo requires wind-photovoltaic-battery setup. 100% RES penetration needs PHS support, while electrochemical storage can achieve 80-90%. Economic viability is ensured with electricity prices of 200-350 €/kWh and investment payback periods of 6-10 years.

The results of this research closely align with the above study in terms of dimensioning optimization of RES and storage system, except for the storage capacity on Astypalaia, which is notably lower in our findings. Additionally, the cost of lithium batteries in the Katsaprakakis et al. (2019) paper is approximately 3 times higher compared to our study (900€/kWh vs. 160€/kWh), primarily due to the age difference of the sources. As a result of these variations, his research indicates higher initial setup costs.

Gioutsos et al., (2018) paper as mentioned in chapter 1.1, offers a relevant comparison to this research. Both studies focus on Rhodes and examine cost optimization. Although the Levelized Cost of Energy (LCOE) curve follows the same pattern with this study, it has some clear differences. In this research the curve is shifted considerably lower in cost and can reach 100% renewable energy penetration, with the optimal scenario at 67% versus 60%. After the calculations of euro-dollar exchange rate for the year 2018 was used, it was found that there is a significant difference in capex for PV and batteries. This can be an explanation about the contrast between the optimal system configurations as Gioutsos findings shows the use of wind at 60% compared to this study that a combination of 30.5% wind, 36.2% solar and 0.3% Biogas mix came out of the simulation. Furthermore, the cost of energy in Gioutsos optimal scenario is very identical to this study, however the fuel cost that uses is far cheaper than the existing one. The addition of Biogas as a form of RES is a novelty and contributions of this research as there are not many that have attempted it in the literature.

The paper of Katsoulakos, (2019) as also mentioned in chapter 2.9 discusses autonomous electrical systems on 61 Greek islands known as Non-Interconnected Islands (NII), where electricity production costs are 2.5 times higher than connected areas. Simulations on Astypalaia Island show that combining renewables and energy storage can reduce high energy expenses. His results, generated using the same HOMER PRO program, indicate significantly lower renewable energy penetration. This discrepancy arises from four primary factors. Initially, his study employs synthetic hourly data for solar and wind resources, differing from the real data used in this research. Additionally, his analysis employs outdated prices for wind turbines and lithium batteries, leading to inflated cost projections compared to current market rates. Lastly, during that period, the relatively lower cost of diesel (0.60 €/l vs 0.92 €/l) diminishes the apparent attractiveness of renewable energy sources.

5.2 Weaknesses and Limitations

While the simulation results presented in the previous chapter provide valuable insights into the cost-optimal configuration of hybrid renewable energy systems for each Greek Non-Interconnected Island, there are some potential small weaknesses to consider.

One weakness is that the simulations are based on assumptions and models, which may not perfectly reflect the real-world conditions on each island. The simulation results should be considered as indicative, and some safety factors should be taken into account, especially in the scenarios of 100% energy autonomy. To address this concern, it is recommended to implement these projects into steps.

Another potential weakness is that the simulations do not consider the variability of renewable energy resources in extreme weather conditions changes within the hour-by-hour variability, which may affect the performance of the hybrid systems. The variability of wind resources may lead to fluctuations in the output of the hybrid system, which may affect the reliability and stability of the electricity supply. More specifically, the biomass data used in the simulations may not be up-to-date or accurate. The availability and quality of biomass resources can vary significantly over time and may depend on a number of factors, such as climatic conditions and land use practices. Furthermore, the simulations do not consider in all the islands the application of biogas as a renewable energy source due to low resource availability. This limitation could potentially affect the accuracy of the results and could prevent the identification of optimal configurations that may include biogas as a renewable energy source. Therefore, future research should focus on updating biomass data and investigating the feasibility of biogas implementation to ensure a more comprehensive and accurate assessment of possible cost-optimal hybrid renewable energy system configurations in the Greek Non-Interconnected Islands.

Furthermore, the simulations do not consider the social and economic impacts of the transition to renewable energy sources on local communities. For example, the implementation of renewable energy systems may lead to changes in the local economy and job market. The implementation of large wind turbines could have significant social impacts on local communities in these islands. The noise generated by the turbines could cause disturbance and affect the quality of life of residents living nearby. In addition, the wind turbines may block the scenic view of the islands, which could affect tourism and the overall cultural heritage of the area. There are many islands that already have restrictions in the type and height of the structures that can be build due to cultural heritage, that local authorities trying to preserve. Additionally, solar panels might not be allowed on rooftops in some Greek islands due to strict architectural guidelines aimed at preserving the traditional and picturesque character of the local buildings and landscapes. In such areas, maintaining the visual harmony and historical aesthetics of the architecture is a priority, and these guidelines may restrict the installation of solar panels that could alter the traditional appearance of rooftops. It is therefore vital to consider the potential social impact of the transition to renewable energy and to engage in local community consultation and dialogue to ensure that all the concerns and needs of these communities are considered alongside the economic benefits of the transition.

Finally, to encompass this specific scenario, simulations were carried out for all islands, excluding the implementation of Wind Turbines and Biogas Generators. The resulting outcomes are presented in the following table. In this particular scenario, the average outcomes reveal a fourfold surge in PV panel capacity (81 MW) compared to the optimized scenario incorporating all renewable energy sources (55 MW). Similarly, the average capacity of Li-Batteries exhibits a corresponding fourfold increase, escalating from 83 MWh to 294 MWh. Consequently, these augmentations lead to a forty percent upswing in the energy cost, rising from an average of 0.101 €/kWh to 0.122 €/kWh. However, a positive aspect of this case is the marginal increment in the Renewable Fraction, which elevates from an average of 81% to 89%.

Table 7: Results for cost-optimal configurations of all island's energy supply systems without Wind Turbines and Biogas Generators.

A/A	Islands	PV (kW)	Existing System		Batteries 1MWh LI (#)	Strategy	NPC (€)	LCOE (€/kWh)	CAPEX (€)	Ren Frac (%)
			Diesel Gen (kW)	HFO / Mazut (kW)						
1	Amorgos	7160	4920		28	CD	15,809,230 €	0.122 €	9,783,926 €	93
2	Astypalaia	5132	4000		21	CD	12,921,720 €	0.137 €	7,179,126 €	89
3	Chios	119300		64452	499	CD	295,889,400 €	0.109 €	168,294,000 €	81
4	Ikaria	25410	5000	9716	100	LF	53,448,980 €	0.122 €	35,647,860 €	99
5	Karpathos	29315	6600	10000	100	LF	67,181,780 €	0.127 €	38,190,420 €	90
6	Kythnos	7928	5200		30	PS	20,787,070 €	0.137 €	11,312,420 €	89
7	Lesvos	187564	31800	49500	693	LF	437,359,000 €	0.113 €	256,576,700 €	92
8	Limnos	43006	3800	18000	167	LF	96,408,620 €	0.114 €	60,049,980 €	96
9	Milos	38052	4000	15000	146	LF	82,818,460 €	0.123 €	52,775,390 €	97
10	Rhodes	631732	119000	186000	2118	LF	1,424,971,000 €	0.115 €	837,206,500 €	93
11	Samos	93483		47000	334	PS	251,200,200 €	0.109 €	130,435,000 €	82
12	Santorini	65914	37039	34878	316	CC	249,457,000 €	0.109 €	106,027,000 €	60
13	Serifos	5703	4900		22	PS	15,131,200 €	0.130 €	8,224,481 €	88
14	Sifnos	15709	9000		60	PS	39,186,300 €	0.137 €	22,377,280 €	91
15	Skyros	11282	6500		46	PS	25,706,270 €	0.122 €	16,135,330 €	95
16	Symi	9789	5000		37	PS	23,792,180 €	0.123 €	13,748,040 €	92

Overall, it is important to acknowledge the limitations and weaknesses of the simulation results presented in this thesis, as they provide a foundation for further research and improvement. Despite the weaknesses identified, the simulation results still offer valuable insights into the cost-optimal configurations of hybrid renewable energy systems for the Non-Interconnected Greek Islands. The results serve as a valuable starting point for policymakers and stakeholders, offering a glimpse into the potential benefits of renewable energy integration. By identifying the most efficient and effective combinations of renewable energy sources, this study lays the groundwork for the implementation of environmentally friendly and economically viable energy systems in the island communities. Moreover, this study thesis contributes to the broader knowledge base on renewable energy integration, specifically tailored to the unique context of the Greek Islands. This localized approach allows for a more accurate assessment of the islands' energy needs, taking into account their specific geographical, climatic, and socio-economic characteristics.

5.3 Challenges and Opportunities

The transition of the Greek Non-Interconnected Islands to hybrid renewable energy systems presents challenges and opportunities. One of the main challenges is the need for a significant initial investment in infrastructure and equipment, as well as the variability of Renewable Energy Sources, which requires energy storage systems, which bear the cost of the transition. Another challenge is finding the appropriate space on the islands for the installation of PV panels and Wind Turbines. Due to the limited land availability and competing land-use priorities such as tourism, identifying suitable locations that optimize energy generation while minimizing environmental and social impacts can be complex. To address the challenge of finding suitable areas for installing PV panels and wind turbines in the selected islands, the thesis project took a proactive approach. The coordinates of resources input data were manually selected in mountainous/rocky areas, specifically chosen for their ample space to accommodate wind turbines and their higher wind speed potential. Additionally, a preliminary dimensioning study was conducted on the above optimized scenario that focuses on utilizing only PV panels, to further calculate the cover area that is needed in relation to the total area of each island. For these estimations, typically commercial PV panel of 500W were selected with area dimensions of about 2.88 square meters. The results across all islands indicate a significantly low percentage of surface area covered by PV panels, relative to the total surface of each island. This suggests that identifying suitable installation locations is not only feasible but also relatively straightforward because there is ample available space on the islands that is not allocated for other purposes.

Table 8: The percentage of coverage in relation to the total surface of each island.

A/A	Islands	PV (kW)	Number of PV Panels	Total Surface Cover Area of PV Panels (km^2)	Percentage Coverage of the Surface Island (%)
1	Amorgos	7160	14321	0.041	0.03
2	Astypalaia	5132	10265	0.030	0.03
3	Chios	119300	238599	0.687	0.08
4	Ikaria	25410	50821	0.146	0.06
5	Karpathos	29315	58631	0.169	0.06
6	Kythnos	7928	15856	0.046	0.05
7	Lesvos	187564	375127	1.080	0.07
8	Limnos	43006	86012	0.248	0.05
9	Milos	38052	76104	0.219	0.15
10	Rhodes	631732	1263463	3.639	0.26
11	Samos	93483	186966	0.538	0.11
12	Santorini	65914	131829	0.380	0.50
13	Serifos	5703	11407	0.033	0.04
14	Sifnos	15709	31417	0.090	0.12
15	Skyros	11282	22564	0.065	0.03
16	Symi	9789	19577	0.056	0.10

However, there are also opportunities such as reduced greenhouse gas emissions and the cost of energy, increased energy independence, and job creation in the renewable energy sector. In addition, the transition can stimulate local economic development and promote sustainable tourism, while protecting the natural beauty and cultural heritage of the islands. Another significant opportunity that arises with the government's plans to interconnect many of these islands is the potential to export the surplus electricity to the mainland. By leveraging the existing renewable energy sources on these islands, Greece can harness this surplus energy and contribute to the greater goal of a clean energy pathway. This export potential not only benefits the islands themselves but also enables the sharing of sustainable energy resources for the overall advancement of Greece's clean energy objectives.

Therefore, it is important to identify and address the challenges while maximizing the opportunities to achieve a successful transition to clean and cheap energy in the Greek Non-Interconnected Islands.

5.4 Policy-Making Recommendations

Overall, the simulation results provide a solid basis for policymakers, investors, and energy stakeholders to make informed decisions about the implementation of cost-optimal hybrid renewable energy systems in each Greek Non-Interconnected Island. By implementing the most optimized RES setup, the islands can achieve their goal of a 60+% share of RES and transition towards clean and cheap energy while also reducing their dependence on imported fossil fuels and contributing to the global effort to combat climate change.

In addition, the Greek government should consider implementing policies and regulations that incentivize and promote the adoption of hybrid renewable energy systems on each island. Such policies could include feed-in tariffs, tax credits and subsidies for the installation of renewable energy systems. A balanced combination of these threes would be highly effective in promoting the widespread adoption of renewable energy systems and achieving a sustainable energy transition. The government could also implement policies requiring a minimum share of renewable energy in each island's energy mix, which would enforce investment in renewable energy and accelerate the transition.

Furthermore, the government should prioritize the modernization and upgrading of the electricity infrastructure in the Greek Non-Interconnected Islands to support the integration of renewable energy systems. The integration of RES into the grid requires the development of smart grids that can efficiently manage their variability and intermittency of them. Thus, the government should invest in the development and deployment of smart grid technologies, including energy storage, demand-side management, and advanced metering infrastructure. Advanced metering infrastructure plays a crucial role in facilitating the integration of renewables by providing real-time data on energy consumption, allowing for more precise monitoring and control of distributed energy resources, and enabling time-of-use pricing strategies that encourage consumers to shift their energy usage to times when renewable sources are abundant, thus reducing the strain on the grid during peak demand periods.

Finally, it is essential for the government to engage with local communities to ensure that the transition toward hybrid renewable energy systems is socially and economically sustainable. The government should involve local communities in the decision-making process, provide information and education about the benefits of renewable energy, and address any concerns or challenges that may arise during the transition. By engaging with local communities, the government can ensure that the transition towards hybrid renewable energy systems is successful and sustainable in the long term.

Chapter 6 Conclusions

6.1 Answer to the Main Research Question

In this study, the objective was to determine the cost-optimal configurations of hybrid renewable energy systems for achieving a substantial share of renewable energy sources (RES) penetration in Greek Non-Interconnected Islands, driving the transition towards clean and affordable energy. By addressing a series of sub-questions and utilizing advanced modeling and simulation tools, a comprehensive analysis was conducted to shed light on the potential and feasibility of renewable energy integration.

The exploration of the current energy systems in Greek islands, notably the Non-Interconnected Islands revealed the heavily reliance on fossil fuels, particularly diesel and heavy fuel oil, due to their geographical isolation and limited access to the mainland electrical grid. Energy costs are extremely higher on these islands, making them dependent on costly fuel imports and posing challenges related to energy security and environmental impact.

In Greece, the potential for renewable energy sources is substantial. Solar power benefits from high solar radiation, particularly in the Greek islands. Wind power holds promise in coastal areas with strong average winds. Biomass and biogas provide opportunities for heat and electricity production, addressing energy and waste management challenges. Geothermal energy sources, both high and medium enthalpy, exist on several islands. Energy storage systems, including pumped hydro storage and batteries, are critical for ensuring a stable energy supply. These findings from various studies demonstrate that Greece and more particular the Greek Non-Interconnected islands have significant potential for harnessing renewable energy sources and implementing energy storage systems to transition towards a more sustainable and autonomous energy landscape.

Through meticulous simulations and data analysis, the research identified valuable insights into the suitability of renewable energy sources for each specific Greek Non-Interconnected Island. Each island's unique characteristics, including size, annual electricity consumption, and resource availability, influenced the choice of RES. Solar panels were favored on smaller islands with consistent sun exposure, while larger islands with higher wind speeds tended to rely more on wind turbines. Biogas was limited in most cases and mainly on the big islands. The exploration of geothermal resources, as exemplified by Milos, further emphasizes the potential for expanding the spectrum of renewable energy solutions. The results for small islands showed, an average energy mix of 7 MW PV and 3 MW Wind Turbines is suggested to optimize the levelized cost of electricity. Medium-sized islands may benefit from 29 MW PV and 18 MW Wind Turbines, while large islands could consider a mix of 86 MW PV and 78 MW Wind Turbines. The capacity of batteries was determined based on the specific energy needs of each island, with an average of 28, 96, and 197 MWh for each island category respectively, ensuring reliable power supply during periods of renewable resource variability. These findings provide crucial information for tailoring the energy systems to the unique circumstances of each island.

The investment requirements for achieving a 60+ percent share of RES on each island were highlighted in the simulations ranging from 6.5 million Euros for the island of Astypalaia up to 605 million Euros for Rhodes Island. The investment primarily involves all the installation of renewable energy infrastructure, as well as the development of energy storage systems. The exact financial needs vary depending on the island's energy consumption, existing energy systems, and the selected RES mix. To fund these investments, a combination of sources could be considered. Government support, in the form of subsidies, tax incentives, and feed-in tariffs, can encourage private investors to participate. European funding and grants focused on clean energy projects can also contribute. Moreover, public-private partnerships and collaboration with international energy companies could facilitate the necessary capital injection. Achieving the transition to a 60+ percent RES share will require a well-thought-out financing strategy that leverages a mix of public and private funds to ensure the sustainability and success of these renewable energy projects in the Greek Non-Interconnected Islands.

In conclusion, this research explores the cost-optimal configuration of hybrid renewable energy systems tailored to each of the Greek Non-Interconnected Islands. The primary objective is to achieve a 60+% share of renewable energy sources and facilitate the islands' transition to cleaner, more cost-effective energy solutions. The study underscores the significance of island-specific RES solutions and the integration of energy storage systems, predominantly batteries, to maintain a stable power supply. Investment requirements for this transition are influenced by island size, energy consumption patterns, and the selected mix of RES. A diverse array of funding sources, including government incentives, international grants, public-private partnerships, and collaboration with energy companies, can be harnessed to support the realization of these optimal configurations. Ultimately, to attain the 60+% RES target, it is essential to adopt island-tailored approaches for RES integration and employ versatile financing strategies to ensure the sustainability and effectiveness of the transition.

6.2 Contribution

The transition to clean and affordable energy is a major challenge for all countries, particularly for Non-Interconnected Islands such as those in Greece. Despite the availability of renewable energy sources, these islands have traditionally relied on fossil fuel-based power generation, resulting in excessive costs and environmental degradation. This research addresses this challenge by examining the cost-optimal configuration of hybrid renewable energy systems for achieving a 60% or greater share of renewable energy in each Greek Non-Interconnected Island while ensuring a transition towards clean and affordable energy. Through simulations and analyses, this research identifies the most optimized renewable energy setups for each island, taking into consideration the availability of solar and wind resources, and provides a roadmap for transitioning to sustainable energy sources. However, the research also highlights the need for further investigation into the social and economic impacts of this transition on local communities and acknowledges the challenges of integrating biogas due to low resources and outdated data. The findings of this research contribute to the literature on renewable energy transitions and offer insights for policymakers and stakeholders in the energy sector in Greece and beyond.

6.3 Limitations and Recommendations for Future Studies

As mentioned above in the chapter 5.2 there are several limitations associated with this research, that could be focus for future research. The analysis of geothermal and biomass energy sources is not exhaustive due to data limitations, making it challenging to provide a comprehensive evaluation of their potential in the context of Greek Non-Interconnected Islands. Furthermore, the research primarily focuses on specific renewable energy sources, such as photovoltaics and onshore wind power, without considering other promising options like ocean-wave power and offshore wind power. The study excludes hydrogen-based storage solutions, which are considered cutting-edge and not yet mature enough for widespread implementation. Additionally, while pumped hydro storage systems are included in the study, their potential may not be fully explored, particularly for large islands that have ample space to accommodate them as a suitable solution for mitigating the intermittency of renewable energy.

Moreover, given the large number of Greek islands, the research primarily concentrates on Non-Interconnected Islands in Greece, as these islands face the most significant energy challenges. As a result, other islands may have different energy characteristics and requirements that were not thoroughly investigated. However, it's important to recognize that there are many islands sharing characteristics similar to those investigated, making it possible to implement similar modified solutions without the need for additional research. On top of that, the limited computing power for the simulation, which may impact the precision of the results and research time limitation. The computational limitations hinder the exploration of a broader range of scenarios and configurations that could yield more refined outcomes. Despite these limitations, the research provides valuable insights into the transition to renewable energy systems in island communities and lays the groundwork for future studies and policy considerations in this area.

Future research should explore untapped renewable energy sources like ocean-wave and offshore wind power to diversify the island's energy portfolio. Additionally, efforts should focus on gathering comprehensive data for geothermal and biomass energy sources to assess their viability more thoroughly. As hydrogen-based storage solutions mature, they should be investigated for integration into island energy systems. Further analysis of pumped hydro storage systems solutions, particularly for larger islands, could enhance energy management. Lastly, expanding research to encompass all Greek islands and their diverse energy characteristics is essential for the energy transition of Greece.

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