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MASTER THESIS

Comparative Assessment of Electrical Generating Systems for a Greek Island

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Abstract

This master thesis is the last part of the master studies in the department of Energy Management and Sustainability, at the Swiss Federal Institute of Technology (EPFL) in Lausanne. This work has been performed in collaboration with the company Renenig Energy, in Athens. The reader should note that the report is an academical work. Results and conclusion are influenced by hypothesis and should not be taken as general truths. The case study is a fictive project but it is composed of values adapted from another real but confidential project, which makes the analysis plausible.

The owner of a private island in Greece wants to build a luxury resort on his island. Therefore, he will also need an electrical generating system that must cover the future electricity demand. Usually, diesel generators are used in remote areas in order to produce electricity. However, this technology is very expensive, and harmful for the environment.

This master thesis covers the estimation of the electricity demand and the technico-economical assessment of different energy systems. The objective is to evaluate the potential of a microgrid composed of different renewable energy technologies and compare it to the a baseline system composed of generators only.

The hourly electricity demand of the entire island has been modeled using a bottom-up approach with a list of representative types of locals. The consumption of these locals have been divided into three categories : The appliances, the lighting and the heating/cooling. For the energy system which must produce electricity, supply strategies have been defined based on the type of technology. For all strategies, an optimization of the technology installed capacities is performed with the software HOMERPro. It is used as a tool to minimize the net present cost of the energy system and analyze the microgrid energetic behavior.

The yearly electricity demand of the island has been estimated to around 11 GWh, with a peak load of 2,5 MW during the summer. The cost of serving this load with generators is $ 63 million with a levelized cost of electricity of 0.467 $/kWh. When integrating solar panels, the system cost decreases to $ 51.3 million with a LCOE of 0.378 $/kWh. Moreover, wind turbines and a battery storage system are also economically viable. The last strategy consists of distributed PV panels on building roofs, wind turbines and a battery storage system. Results show that this energy system can decrease the cost to $ 39.8 million while emitting half of the carbon dioxide compared with the baseline system. However, the battery bank has a large impact on CO_2 emissions due to its manufacturing processes.

Further work can be done for this case study, especially on the network stability assessment, which was not part of this master thesis. Moreover, the potential of implementing hydrogen in the microgrid could be interesting. This could bring a good storage alternative to batteries.

Acknowledgements

This master thesis opportunity has been given by Renemig Energy, and more precisely by Niko A. ILIADIS, co-founder of the company. I sincerely thank him for having shared with me his strong technical skills and knowledge in the field of energy systems and economical optimization. His help has been very important in order to understand the Greek energy market and its potential for renewables. Its hospitality enabled me to feel comfortable during the time spent in Athens, giving me the chance to focus on the thesis.

Furthermore, I want to thank my fellow office partners Nolwenn Barbé, Luc Prioretti, and Brice Boissonneault for their help in discussions about general concepts as well as technical advises. I appreciated to have different opinions and ideas when analyzing my results and strategies.

Finally, I want to thank professor Edgard Gnansounou for having given me the opportunity to work on a tangible case study in my field of interests. His experience in leading scientific projects helped me defining the scope of the master thesis and consistent objectives in terms of analysis. His strong knowledge in energy planning helped me questioning myself on scenarios and strategies assessments, which was the core of the technico-economic analysis performed during the master thesis.

Contents

List of Abbreviations

BESS	**B**attery **E**nergy **S**torage **S**ystem
COP	**C**oefficient **O**f **P**erformance
DER	**D**istributed **E**nergy **R**esources
DoD	**D**epth **o**f **D**ischarge
EER	**E**nergy **E**fficiency **R**ating
EV	**E**lectric **V**ehicles
HEDNO	**H**ellenic **E**lectricity **D**istribution **N**etwork **O**perator
LCOE	**L**evelized **C**ost **O**f **E**nergy
LHV	**L**ower **H**eating **V**alue
NPC	**N**et **P**resent **C**ost
NPV	**N**et **P**resent **V**alue
PV	**P**hoto**v**oltaic
RES	**R**enewable **E**nergy **S**ources
SoC	**S**tate **o**f **C**harge
STC	**S**tandard **T**est **C**onditions

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1 Introduction

The owner of a private island in Greece wants to build and develop a luxury resort on its island. Therefore, he will also need an electrical generating system that must cover the future electricity demand. This master thesis covers the estimation of the electricity demand and the technico-economical assessment of different energy systems. The first part of the thesis has been spent in Athens, at Renemig Energy Company. Then, the rest of the study as been performed in the Bioenergy and Energy Planning Research Group at EPFL.

1.1 Context

Arkoudi island is a small, private and inhabited island on the Ionian Sea (Greece). The owner of the place wants to develop a luxury resort which could accommodate guests throughout the year. Therefore, he has to provide an energy system that would allow the resort to operate in good conditions in term of reliability and costs. The entire island is covered with trees and nothing is built on site. The architecture office, in charge of the project, has asked to integrate the renewables at the maximum possible in the structures and other areas.

Figure 1: Geographical location of Arkoudi and its topography [1]

1.2 Problem

The electricity network in Greece consists of two main sectors: the interconnected and the non-interconnected. The non-interconnected network is composed of 32 sub-systems in the Greek islands. Greece has a generation mix consisting of lignite, natural gas, heavy fuel oil and renewables. However, in the non-interconnected system, the penetration of renewable energy is significantly lower than in the interconnected system because of the limitations such as electricity storage or geographical constraints. More specifically, the islands are considered as microgrids with a generation mix consisting of heavy fuel oil and diesel, with low efficiency, limited flexibility and high dependency on the oil market. Hence the cost of operation varies between 0.1 – 4.00 EUR/kWh with very high emissions [2].

The Hellenic Electricity Distribution Network Operator (HEDNO), under the advice of the European Union has created a framework for the participation of independent power producers providing renewable energy in combination with storage to provide dispatchable power to the island network.

1.3 Aim of the master thesis

Considering the above information, the objective of this study is to design the optimally technical and financial power system for an independent power producer. The goal is to consider multiple electricity generation alternatives in order to design an optimal system.

The main tasks that needs to be performed are the following :

1. Estimation of the electricity demand
2. Technologies potential assessment
3. Technico-economical assessment of energy systems
4. Discussion and recommendations

1.4 Scope boundaries

The detailed electrical design of each component of the microgrid is not part of the thesis. The main purpose is to have an understanding on the potential of different energy sources and perform a technico-economical assessment of a microgrid on Arkoudi island. The task is to propose the best combination of generation units that would ensure the microgrid to be feasible, economical, robust and environmentally friendly.

2 Methodology

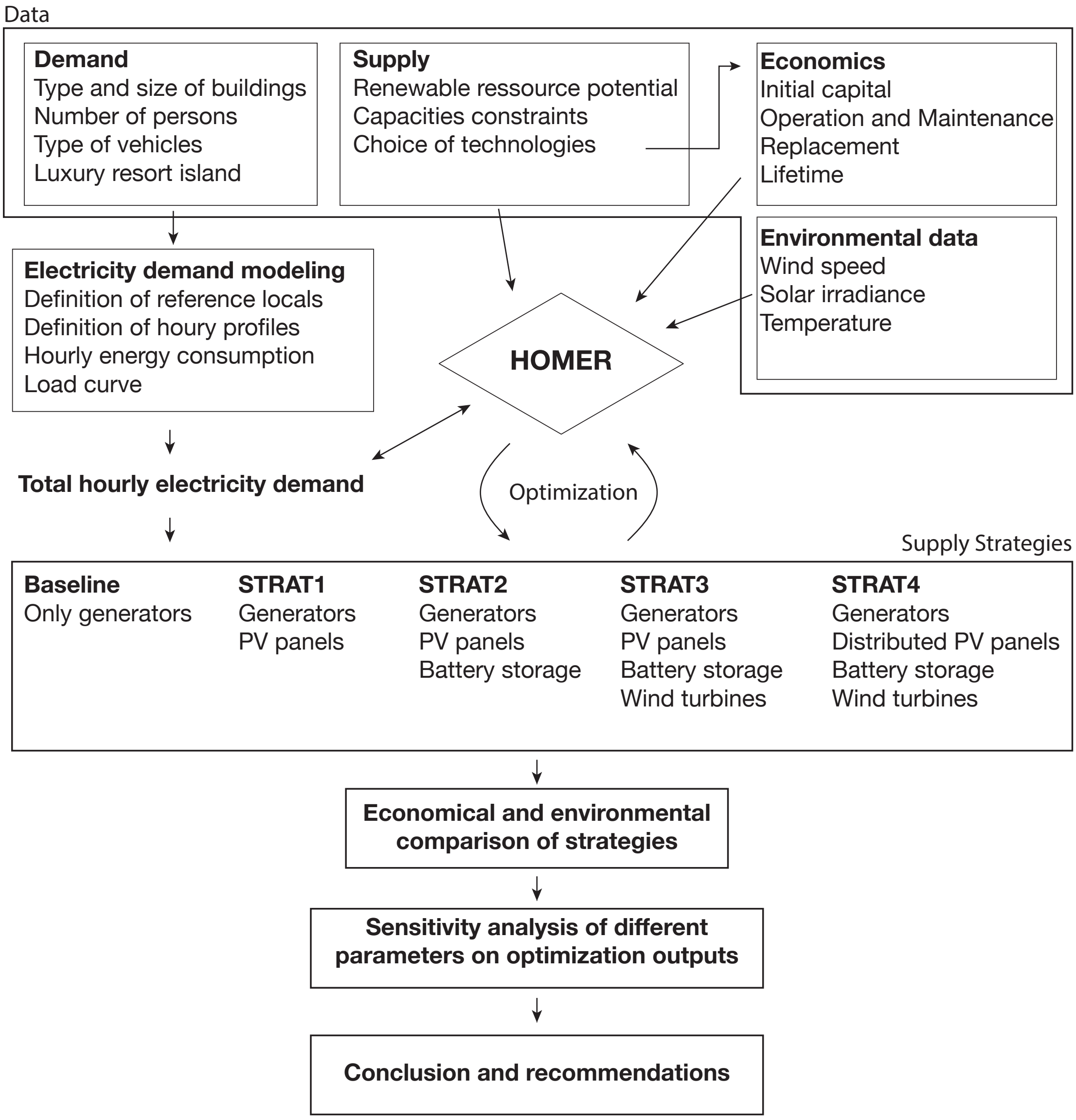


Figure 2: Methodology description of the master thesis.

2.1 Data

The first step of the master thesis was to collect input data for the project. This has been possible thanks to Renemig company which has experience in such projects (island electrification). Therefore, the type of planned buildings, their size and the number of people that will visit the island have been given by the company.

2.2 Electricity demand

The total electricity demand of the island needs to be estimated on a hourly basis in order to optimize the use of intermittent sources of electricity such as renewables. In order to do so, a bottom-up approach has been performed by using reference locals and hourly profiles for equipment. This is explained in more details in subsection 4.1.

2.3 Supply strategies

In order to serve the electricity demand, different technologies can be used to produce electricity. The objective is to integrate the renewables as much as possible. As a baseline scenario, an energy system composed of only generators has been designed. Then, renewable sources of energy have been added successively and their integration as been evaluated.

2.4 Optimization

The objective of the project is to design an energy system which has the lowest cost over its lifetime. In order to optimize the installation capacities of different energy components, the software HOMER is used as a tool to evaluate the several strategies.

The abbreviation HOMER stands for Hybrid Optimization Model for Multiple Energy Resources and it was developed at the U.S.National Renewable Energy Laboratory [3]. HOMER allows simulations of grid-connected or off-grid microgrids and includes multiple energy components such as PV modules, wind turbines, batteries, generators, the grid, biomass, hydropower, etc.

Concerning the optimization model, HOMER simulates all feasible combinations of technologies and sizes input by the user, the "best" (according to HOMER) system being the one minimizing the net present cost. Instead of considering a search space, HOMER can also precisely optimize the size of the energy system components if asked by the user. Calculations account for costs such as investment, replacement, operation and maintenance, fuel and interests.

For each hour of the year, HOMER tries to balances the electrical demand with the electricity produced by the system in the most economical way. Therefore, costs and properties of the technologies are the main drivers for the simulation results. The hourly optimization also means that short term related problems such as network stability or demand response are not considered in the optimization.

2.5 Comparison, discussion and conclusions

The strategies will have different production mixes, costs and environmental impact. On top of that, some parameters have to be estimated and therefore a sensitivity analysis has been performed to evaluate the impact of value deviation for some parameters.

3 State of the Art

3.1 Technology review

3.1.1 Diesel generators

Diesel generators use the energy of fuel combustion to run an alternator and produce electricity. It is a well-known technology, which allows to produce power everywhere at anytime, as long as fuel is available. It is often used in remote areas where there is no access to the grid or as a backup source of electricity in case of grid failure.

However, its cost of electricity production is higher than most of the common electricity generation systems and its environmental impact is large due to carbon emissions. In the present context of cost reduction and especially environmental impact reduction, the use of this technology tends to be minimized. Moreover, the high dependence on fuel price makes the use of generators to be sometimes financially risky.

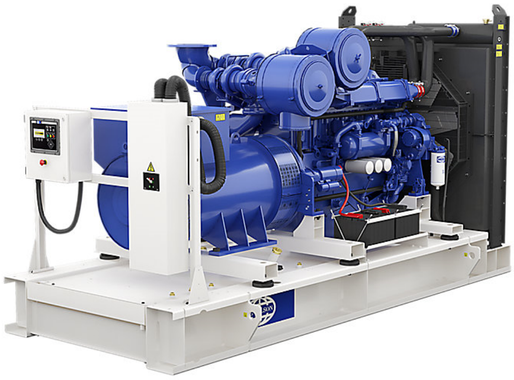


Figure 3: Generator FG Wilson P800P1 - 640 kW, used in this master thesis.

Working principle

The working principle of a diesel generator is not complicated. The fuel is compressed in its restricted volume until it explodes (auto-ignition process) to give energy to the piston. The multiple pistons are connected to a camshaft which allows to transform the linear displacement of pistons to a circular rotation, which is connected to an alternator. The alternator is a electrical generator that converts the mechanical energy into electricity by the use of electromagnetism, [4].

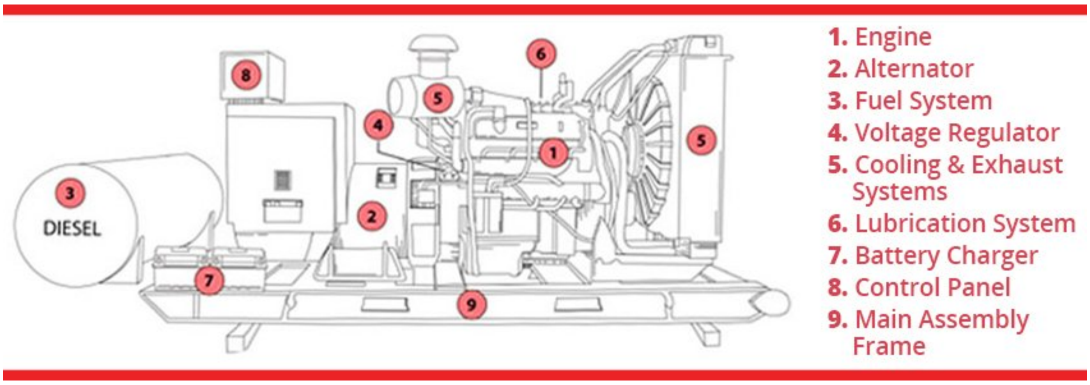


Figure 4: Typical components of a diesel generators

Generators can run as "prime" or "standby", for which they have different characteristics. The prime operation holds for a generator that is used as baseload and which has most of the time a constant power output. Standby operations holds for specific applications such as back-up or when serving peak loads during a limited operating time. The generator is able to produce slightly more power in this mode due to the limited duration. Indeed, after a certain time, the generator would overheat and power output will need to be decreased.

Generators are designed to be the most efficient at around 75 to 80 % of their nominal power, which means that for a park of several generators, there is a need or an opportunity of a synchronization system which will optimize the overall fuel consumption.

3.1.2 Photovoltaic panels

Photovoltaic panels transforms the sunlight energy into electricity. Their first application was in the space for satellites. Nowadays, there is a enormous growth of solar panels installations due to the economical advantages and the seak of an energy transition to renewable energies. In 2017, around 400 GWp of installed power had been installed worldwide (Figure 5).

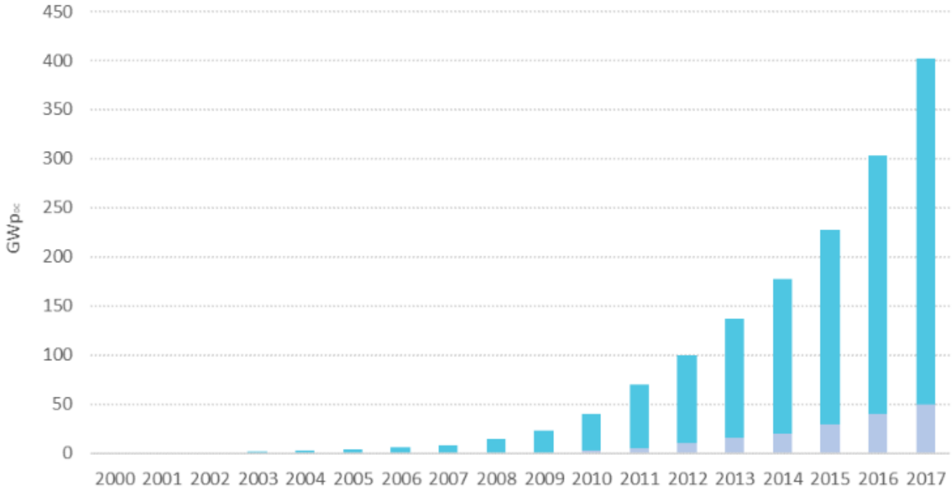


Figure 5: Installation capacity of PV panels worldwide. [5]

There can be multiple types of solar panels technologies such as monocrystalline, polycrystalline, thin film or the recent perovksite technology. However, monocrystalline panels are by far (around 85-90% [5]) the most utilized technology due to good price versus efficiency and its very good stability.

Working principle
The solar cell is a solid-state electrical device (p-n junction) that converts the energy of light directly into electricity (direct current (DC)) using the photovoltaic effect. The process of conversion first requires a material which absorbs the solar energy (photon), and then raises an electron to a higher energy state. This high-energy electron then flows in an external circuit. Silicon is one material that uses this process [6].

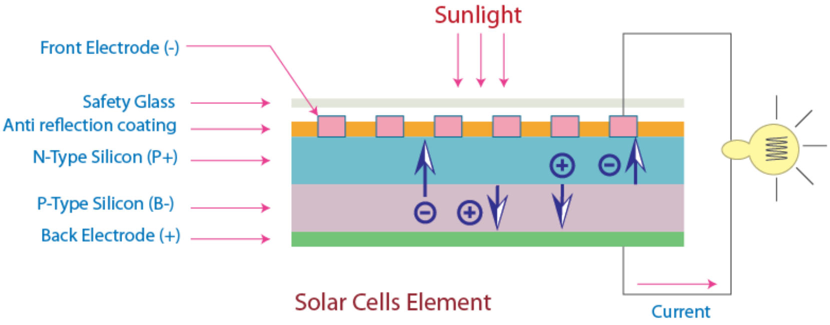


Figure 6: Illustration of the working principle of a solar cell.

However, a solar cell alone does not produce enough power and needs to be connected in series to form a solar module. Then, the solar modules themselves will be connected in series and in parallel before being connected to a solar inverter, which will transform the DC current into AC current. The current can then be injected into the grid or used on site. If the load requires DC current, the modules will be only connected to a charge controller and the current will remain direct current.

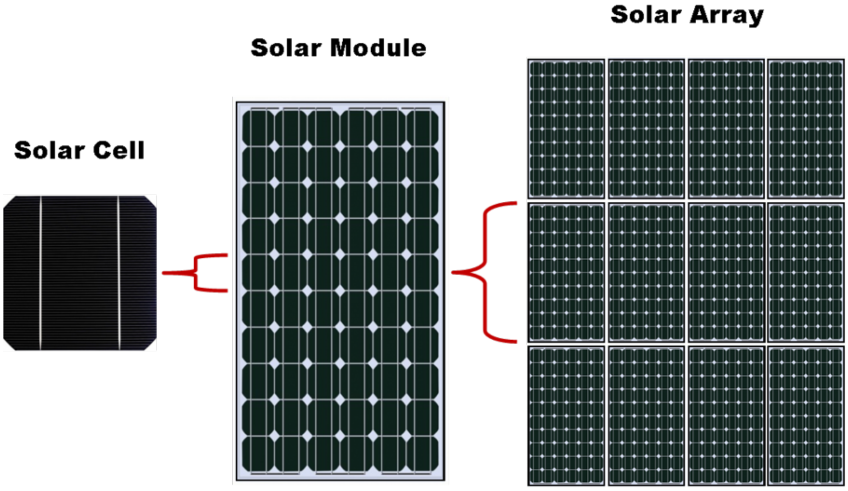


Figure 7: From the cell to the module. [7].

There are now a increasing number of applications for solar panels. For the purpose of this thesis, only 3 applications are considered :

1. A plant of fixed tilted panels
2. A plant of panels with a tracking system (see subsubsection 4.2.2)
3. Distributed installations on building roofs

Shading issues

Shading issues is one of the main concern when designing a solar plant. The related losses are not proportional to the shaded area. In fact, only a small shaded area can drastically reduce the total power output of the installation.

PV modules are built with a number of cells connected in series. Therefore the current flows in all cells and is equal to the cell where there is the least current. If one cell is shaded, it will not produce any current and it will affect all connected cells. Figure 8 shows this principle. Here, there are three by-pass diodes. These diodes allow the current to avoid shaded area in order to limit the loss of electricity production. However, it can been seen that this small leaf makes the panel loose one third of its output power.

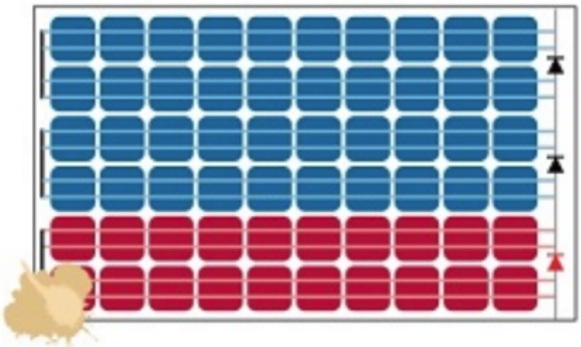


Figure 8: Impact of one shaded cell on the other cells in series.

Consequently, shading has to be taken into account when implementing a solar plant. For example, PV panels should not be installed too close to a high wind turbine. In order to assess the shading area, one has to consider the sun elevation, the azimuth and the height of the object creating the shadow. The elevation and the object height will give the length of the shadow and the azimuth will give the angle. Calculation are explained below has has been performed for the solstices and the equinox.

$$L = \frac{h}{tan(\gamma)} \tag{1}$$

$$\beta = 180 - \phi \tag{2}$$

where

γ	Sun elevation [°]
h	Object height
ϕ	Azimuth angle [°]

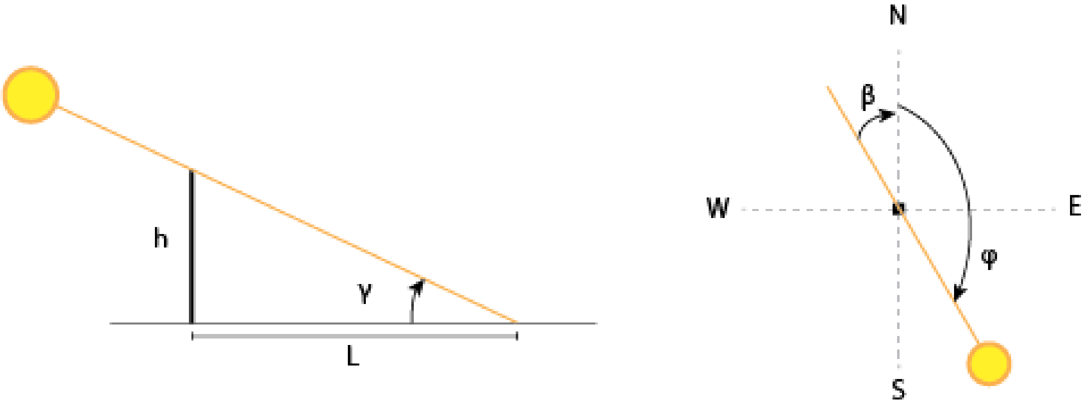


Figure 9: Representation of sun azimuth and sun elevation.

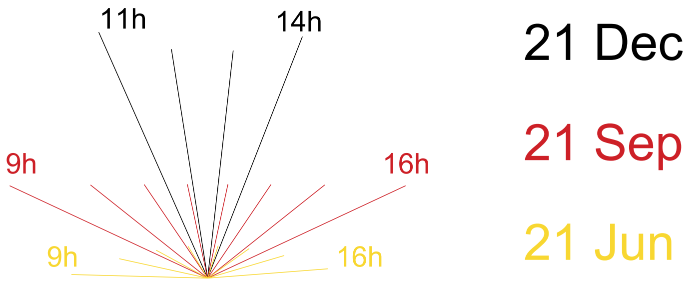


Figure 10: Shading pattern of one stick (the scale depends on the stick height).

3.1.3 Wind turbines

A wind turbine converts the kinetic energy of wind into electricity. The first turbine connected to a utility grid has been installed in 1951 in the UK. In the following decades, oil-based centralized plants have eliminated the technology because of its intermittency and higher cost of operation. However, since the environmental and availability issue of oil has appeared, an exponential number of wind turbines are installed every year in order to increase renewables in the electricity mix.

They exist in different types such as with a vertical axis, a horizontal axis, or with various types of blades, the most common design being the horizontal axis with three blades.

Their sizes vary depending on the application and the location. Small domestic turbines are only several kWs while large wind turbines can reach up to several MWs and 100m height.

Working principle

The wind turbine transforms first the wind linear kinetic energy into rotational energy thanks to the rotor blades. Rotor blades for wind turbines are similar to the wings of an airplane, but unlike wings they have a twisted profile [8]. The blade pitch control modifies the so-called pitch angle which corresponds to the angle of attack of the blade. By increasing or decreasing the angle, the power output can be controlled.

A gearbox is typically used in a wind turbine to increase rotational speed from a low-speed rotor to a higher speed electrical generator [9]. A common ratio is about 90:1, with a rate 16.7 rpm input from the rotor to 1,500 rpm output for the generator.

After the blades and the gearbox, the third most important component is the generator which will transform the mechanical energy from the high-speed rotor into electricity. After that, the current will usually flow through a transformer in order to increase the voltage and distribute the electricity at higher efficiency.

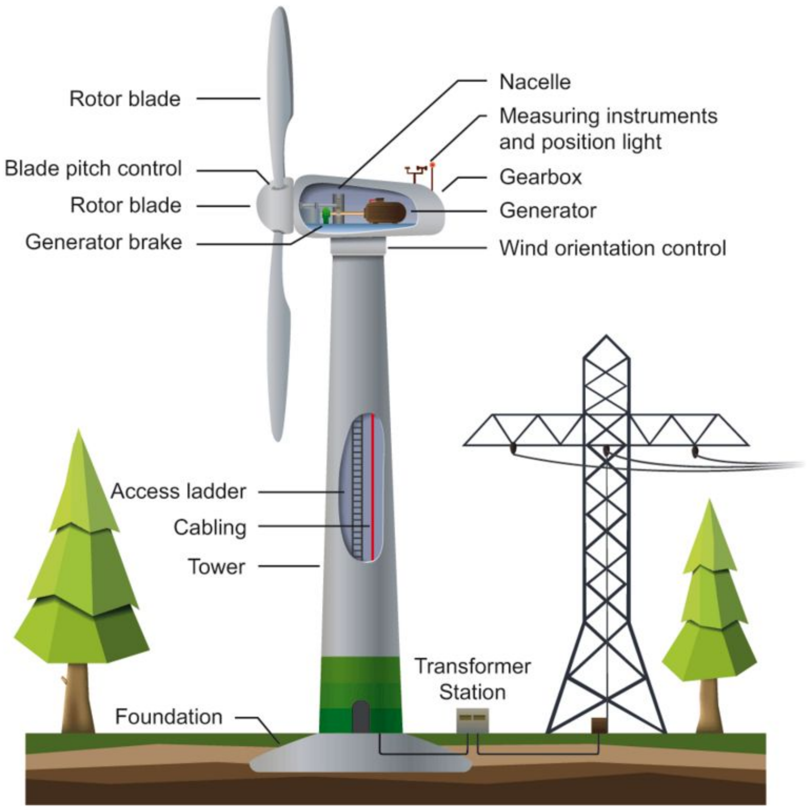
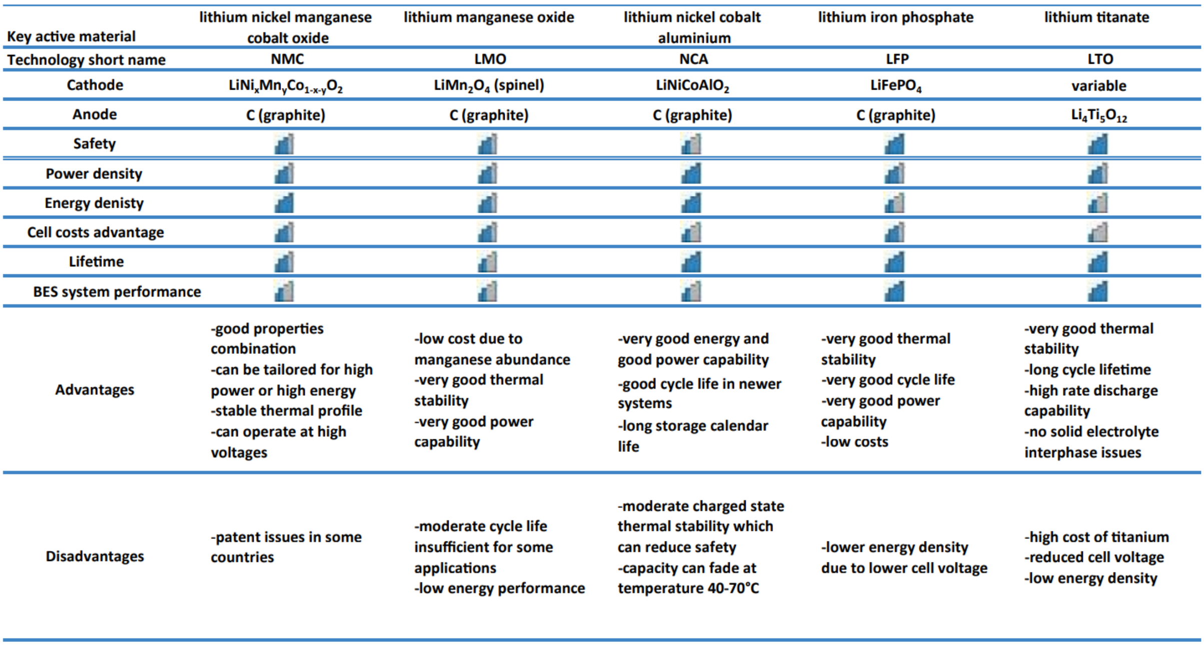


Figure 11: Typical components of a wind turbine [8]

3.1.4 Battery storage

The field of battery technologies consists of various different technologies such as lead-acid, high temperature, flow and lithium-ion batteries. Each of them have different characteristics and applications. An island system designed to operate predominantly on renewable energy requires many services that have to be supplied by the storage system: enhanced frequency responses/frequency containment reserves, frequency restoration reserves and energy shifting. Since there is no potential for pumped hydraulic storage (PHS), batteries need to be performing and flexible in their operation. The high round-trip efficiency and depth of discharge of lithium-ion batteries make them suitable for this island storage application. Moreover, they are well suited for project where higher power needs to be delivered, which is the case when there is a high penetration of renewable energies. As the costs of Li-ion battery systems decline, they are increasingly becoming an economic option for stationary applications, and their presence in that segment is increasing [10].

Lithium-ion batteries are often taken as a single entity but there are various material combinations in the lithium-ion group, leading to unique performance, cost and safety characteristics. The chemistry choice often relates to the desire to optimize the BES system to meet various performance or operational objectives, and such considerations may lead to a different electrode (or electrolyte) material selections [10]. Figure 12 summarizes these differences. It can be seen that the lithium iron phosphate (LFP) would be the most relevant technology for Arkoudi island. Indeed, the main disadvantage of this technology is the lower energy density, which is not a important criterion for the project. Moreover, it has the best results for safety, lifetime and BES system performances.



Key active material	lithium nickel manganese cobalt oxide	lithium manganese oxide	lithium nickel cobalt aluminium	lithium iron phosphate	lithium titanate
Technology short name	NMC	LMO	NCA	LFP	LTO
Cathode	$LiNi_xMn_yCo_{1-x-y}O_2$	$LiMn_2O_4$ (spinel)	$LiNiCoAlO_2$	$LiFePO_4$	variable
Anode	C (graphite)	C (graphite)	C (graphite)	C (graphite)	$Li_4Ti_5O_{12}$
Safety	▮▮▮▯	▮▮▮▯	▮▮▯▯	▮▮▮▮	▮▮▮▮
Power density	▮▮▮▯	▮▮▮▯	▮▮▮▮	▮▮▮▯	▮▮▮▯
Energy denisty	▮▮▮▮	▮▮▮▯	▮▮▮▮	▮▮▯▯	▮▮▯▯
Cell costs advantage	▮▮▮▯	▮▮▮▯	▮▮▯▯	▮▮▮▯	▮▯▯▯
Lifetime	▮▮▮▯	▮▮▯▯	▮▮▮▮	▮▮▮▮	▮▮▮▮
BES system performance	▮▮▯▯	▮▮▯▯	▮▮▯▯	▮▮▮▮	▮▮▮▮
Advantages	-good properties combination -can be tailored for high power or high energy -stable thermal profile -can operate at high voltages	-low cost due to manganese abundance -very good thermal stability -very good power capability	-very good energy and good power capability -good cycle life in newer systems -long storage calendar life	-very good thermal stability -very good cycle life -very good power capability -low costs	-very good thermal stability -long cycle lifetime -high rate discharge capability -no solid electrolyte interphase issues
Disadvantages	-patent issues in some countries	-moderate cycle life insufficient for some applications -low energy performance	-moderate charged state thermal stability which can reduce safety -capacity can fade at temperature 40-70°C	-lower energy density due to lower cell voltage	-high cost of titanium -reduced cell voltage -low energy density

Figure 12: Comparison of lithium-ion chemistry properties, advantages and disadvantages [10].

Working principle

The lithium ion batteries works as an electrochemical device with a positive and a negative electrode. Chemical reactions occur on both sides and a electrical current flows through an external circuit current. On the positive electrode, the following chemical reaction takes place on a aluminum terminal :

$$LiFePO_4 \longleftrightarrow FePO_4 + Li^+ + e^- \tag{3}$$

On the negative electrode, the following chemical reaction takes place on a copper terminal :

$$Li^+ + e^- + C \longleftrightarrow LiC_6 \tag{4}$$

When the battery is being charged, the equations go from left to right. When the battery is discharged, the equations go from right to left. In order for the lithium ions to flow from one electrode to the other, a electrolyte based on $LiPF_6$ is used. An illustration of the working principle is shown in Figure 13.

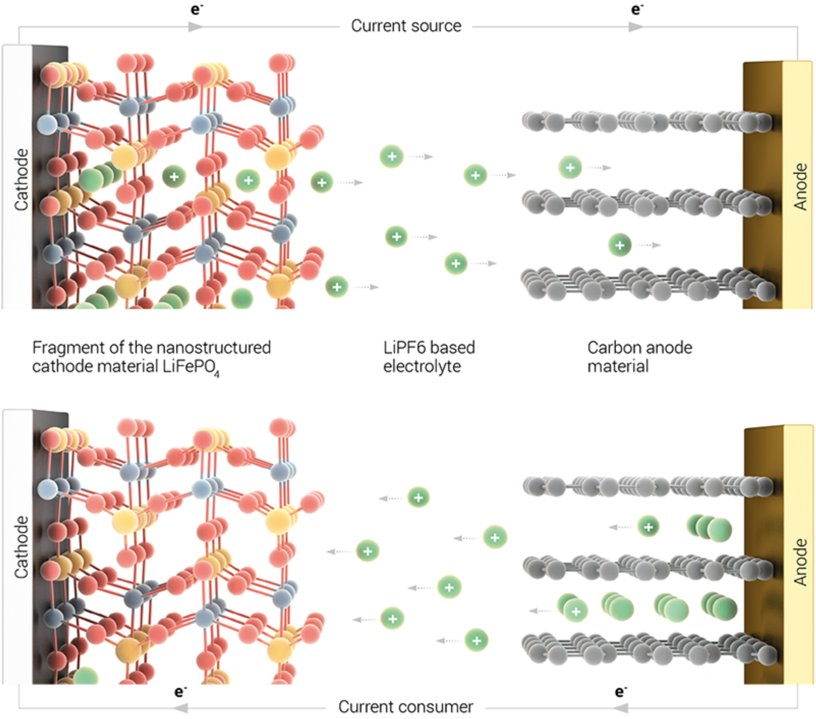


Figure 13: Illustration of the LFP working principle, [11].

The battery cell described above is then connected in series with other similar cells to form a battery pack. An example of a battery pack is the battery of petrol-powered car which is often formed by 6 lead-acid cells of 2V each. For larger application such as for an island electrification, battery packs will by connected both in series and in parallel to form a battery bank.

The battery management system
When the energy system uses a battery bank, there must be a battery management system whose main objectives are to ([12]):

- Protect the application user
- Protect the battery pack itself
- Maximize the performance (power and energy) delivered by the battery
- Maximize the lifetime of the battery pack itself

These objectives can be achieved by electronics and good algorithms designs. On top of the users protection, there will be an optimization of the trade-off between performance and the battery bank lifetime.

3.2 Microgrids

3.2.1 Concept definition

The microgrid, as defined by the U.S. Department of Energy, is a "group of interconnected loads and Distributed Energy Resources (DERs) with clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid and can connect and disconnect from the grid to enable it to operate in both grid-connected or island modes [13]. Microgrids can be classified in four categories [14],[15]:

Large grid-connected microgrids, such as military bases and large campus applications, are connected to a traditional utility, but capable of operating in island mode. The focus of campus microgrids is aggregating existing on-site generation with multiple loads that located in tight geography in which the owner easily manages them.

Community microgrids can serve a few up to thousands of customers and support the penetration of local energy (electricity, heating, and cooling). In a community microgrid, some houses may have some renewable sources that can supply their demand as well as that of their neighbors within the same community. The community microgrid may also have a centralized or several distributed energy storage systems.

Small grid-connected microgrids have a single set of generators, but the latter is supplemented with storage and renewables. Grid-connected microgrids are typically in developing countries with unreliable grids where the backup generator is used frequently.

Remote off-grid microgrids never connect to the main grid and instead operate in an island mode at all times because of economic issues or geographical position. Typically, an "off-grid" microgrid is built in areas that are far distant from any transmission and distribution infrastructure and, therefore, have no connection to the utility grid, [16]. Studies have demonstrated that operating a remote area or islands' off-grid microgrids, that are dominated by renewable sources, will reduce the levelized cost of electricity production over the life of such microgrid projects.[17]

3.2.2 Advantages and challenges

In grid-connected modes, microgrids can make a better use of local energy resources by supplying efficiently nearby loads. In case of grid failure, the microgrid can add reliability to its community and provide them with power. The use of DERs allows to increase local demand without necessarily redesign the grid distribution capacity. For off-grid microgrid, the main advantage lies in the use of cheap and clean renewable solutions. The cost of electricity and emissions can therefore be reduced. In some cases, several off-grids microgrids can connect, take benefits of their respective key strength and try to improve their weaknesses.

The relative small scale of microgrids and the integration of DERs lead to operating challenges. Indeed, intermittent renewable sources and their sharp variations cause power shortfall or excessive generation in those microgrids. Due to the very low inertia of the power network, this variations will immediately results in voltage or frequency deviation. Efficient storage solutions or microgrid interconnections can help increasing stability [18]. The critical demand/supply balance requires both a diversified energy system and a performing control. Load management is a solution to avoid high peak demand by defining deferrable loads.

3.2.3 Existing off-grid systems and pilot projects

The thesis will focus on off-grid solutions therefore this section will describe examples for this type of microgrid. Off-grid system's technology is very old and has been widely used. However, high costs, oil dependency and emissions impact have made these systems economically less reliable and environmentally unfriendly. Their operators are trying to bring cleaner and cheaper energy by the use of renewables.

Eigg island's microgrid is one example success story in microgrid design [19]. Installation was completed in 2008, funded partly by the European Regional Development Fund. The Isle of Eigg with its 90 residents and 31 square kilometers were highly dependent on their individual diesel generators to produce their electricity and a few private mini-hydro systems. The microgrid project was highly successful at integrating multiple renewable energy sources into an island-wide community system, and reducing diesel generator use:

- 110 kW of hydro power with one large 100 kW generator and two small generators.
- 24 kW from four wind turbines
- 32 kW of PV.

The introduction of renewable on-site energy sources was also supported by better load management with energy monitors installed in all properties. Since the launch of the full microgrid in 2008, electricity is available 24 hours a day at reduced costs and 95% of it comes from renewable resources.

Pilot projects are growing in the Greek islands. The main objective is to increase the renewable share in the electricity mix of diesel dependent systems. They are building innovating storage solutions and island interconnection with the ultimate goal of interconnecting all main islands [2].

TILOS (Technology Innovation for the Local Scale Optimum Integration of Battery Energy Storage) project is a Horizon 2020 EU funded project located in the island of Tilos. Tilos is an island of the Dodecanese complex. It is interconnected with Kos island. [20].

The main objective of TILOS project, whose operations have started in Autumn 2018, is the development and operation of a prototype battery system based on NaNiCl2 batteries (2,4MWh) with wind turbines (800 kW) and PVs (160 kW), provided with an optimum, real-environment smart grid control system and with the challenge of supporting multiple tasks including:

- Microgrid energy management
- Maximization of RES penetration
- Grid stability
- Ancillary services to the main grid of Kos

The European Commission says Tilos will be the first autonomous renewable green island in the Mediterranean. It plans to use the project as a blueprint for other small islands across the European Union that have limited grid connection to the mainland. The EU has largely funded the project, providing 11 million euros of the total 13.7 million-euro cost [21].

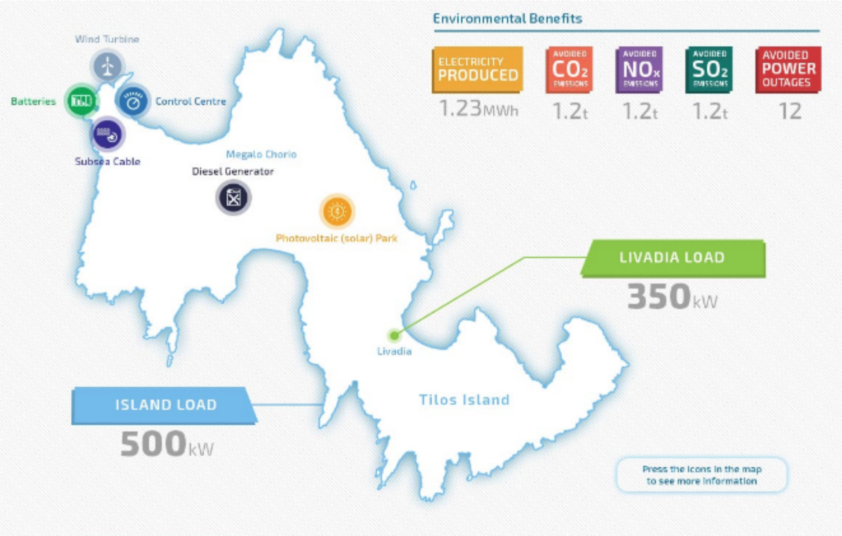


Figure 14: Overview of Tilos microgrid [20]

4 Modeling

4.1 Electricity demand

The total electricity demand of the island has been estimated on a hourly basis, so that the implementation of a microgrid with multiple technologies can be optimized, depending on the intermittency of the production. The hourly basis is a trade-off between a minute basis which is more precise but more complex and a monthly or yearly basis which is not relevant when optimizing the integration of intermittent source of electricity.

In order to better describe future buildings planned on the island and due to the very poor amount of information concerning these constructions and their consumption, representative locals (such as bedrooms, offices, warehouses, etc...) have been defined and can be found in Appendix A, Appendix B and Appendix C. Each of these locals is divided into three different categories of electrical load that need to be separately estimated :

- Appliances
- Lighting
- Heating and Cooling

For the three categories, each representative local has its own consumption in W/m^2 and a daily utilization profile (see Appendix A). This referencing process can be seen as a "load inventory". In fact, all types of loads on the island are given two attributes : the type of local they can refer to and a size factor. For most of the locals, the size factor is given in square meters. For charging stations for example, the size factor is the number of units and this multiplies the unit consumption in W/unit instead of W/m^2.

4.1.1 Appliances

Appliances electricity consumption represents all the need for electrical utilities whose application is different than space heating/cooling or lighting.

Specific consumption have been estimated in W/m^2 thanks to the experience of Renemig. For electric vehicles charging stations, the specific consumption is given in W/unit.

Each local has the following attributes :

- Hourly mean power $P_{a,mean}$ at full utilization [W/m^2]
- Utilization daily profile [-]

The hourly mean power takes into account that all of the equipment is not necessarily used at the same time and during one entire hour. The visual explanation is shown in Figure 15.

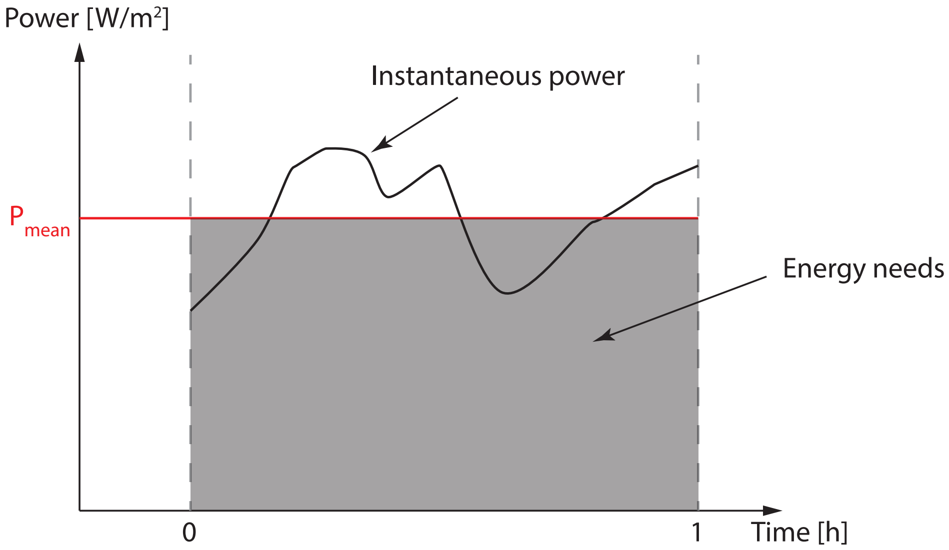


Figure 15: Visual representation of the hourly mean power.

The utilization profile defines how the appliances of the respective local is used during the day. The value is comprised between 0 and 1 where 0 means that no electricity is used in the local during the hour and 1 means that the mean power at full utilization is used. An example of the utilization profile in shown in figure Figure 16.

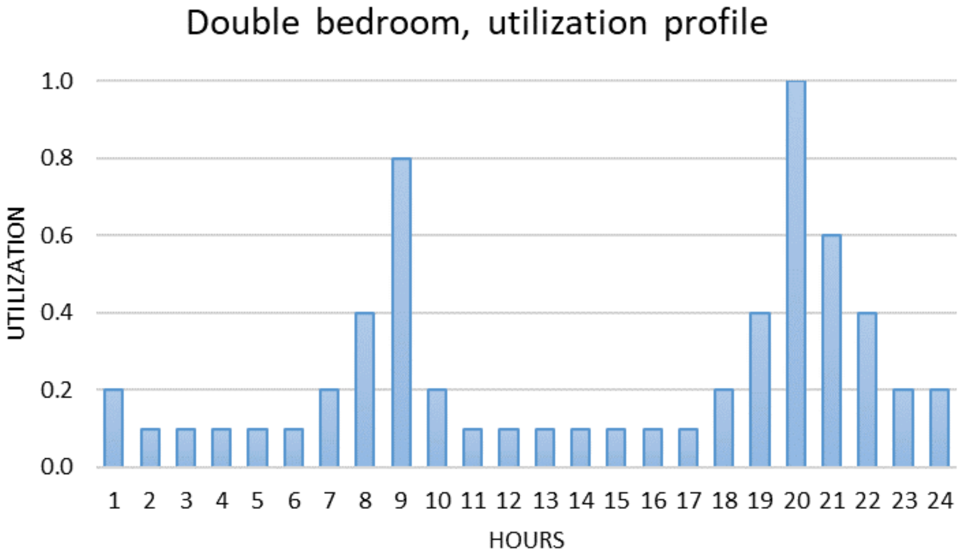


Figure 16: Estimated daily utilization profile for a hotel double bedroom.

Finally, the appliances electricity demand needs can be calculated for each local at each hour i with the following equation :

$$P_{A,i}\ [W/m^2] = P_{a,mean}\ [W/m^2] \cdot \text{Utilization profile}_i\ [-] \tag{5}$$

4.1.2 Lighting

Real lighting consumption depends on factors such as the required illuminance, luminaries efficiency, seasonality or automatizing technologies. In order to simplify the calculation of hourly demands, each local has the following attributes :

- Required illuminance E_m [LUX]
- Luminaries efficiency η_L [lm/W]
- Utilance η_u [-]
- Design factor $p_L = 1.25$ [-]
- Daily utilization profile [-]

The client has defined illuminance required for each type of local. Due to the early stage of the project and for simplification purposes, only one average seasonality profile is defined. The luminaries efficiency will be the same for all locals and consist of LED lights. Utilance is the ratio between received luminous flux versus emitted the flux emitted by the lamp.

The lighting power need can be calculated for each local and each hour i with the following equation [22] :

$$P_{L,i}\ [W/m^2] = \frac{E_m \cdot p_L}{\eta_L \cdot \eta_u} \cdot \text{Utilization profile}_i\ [-] \tag{6}$$

4.1.3 Space Heating/Cooling

Space heating or cooling will be provided by reversible heat pumps, which will serve both heating and cooling loads. The objective is to estimate the hourly demand throughout the year. An average U-value is applied to all buildings of the island since no detailed information is available. Heating and cooling demand depends on the outside temperature. Thus, in order to get an hourly profile for the whole year, the degree-hour methodology is applied. The simplified equation reads :

$$P_{heat,i}\ [W_{heat}/m^2] = k_{th} \cdot \text{DH}_i \tag{7}$$

where

k_{th} Thermal losses in W/(m^{2}K)
DH_i Degree-hours at hour i

The concept of degree-hour

The degree-hour at the hour i is defined as the difference (in absolute value) in temperature between the base temperature T_0 and the actual temperature T_i :

$$\text{Degree-hour}_i\ [K] = |T_0 - T_i| \tag{8}$$

The "base" or "balance" temperature T_0 is defined as the outdoor limit temperature at which

the building requires neither heating nor cooling. Since the temperature requirement in buildings vary between summer and winter, a heating base temperature T$_{h,0}$ and a cooling base temperature T$_{c,0}$ have to be defined. This basically means that the thermostats setpoints for heating and cooling are not the same. It has been shown in [23] that with an outdoor temperature of 18.3 °C, the heat losses are balanced by internal gains and a temperature of 20 °C is maintained inside. The author mentioned that with actual isolation, the 18.3 °C gives overestimated values and that a temperature of 18 °C should be chosen.
In order to consider appliance and solar heat gains, the heating and cooling base temperatures are both decreased by 2°C. The client wants a indoor temperature of 20 °C in winter and 23 °C in summer. The base temperatures are therefore :

$$T_{h,0} = 20 - 2 = 18\ ^{\circ}C \tag{9}$$

$$T_{c,0} = 23 - 2 = 21\ ^{\circ}C \tag{10}$$

Figure 17 shows the visual representation of degree hours. The temperature difference above the cooling base temperature and below the heating base temperature are respectively cooling degree hours and heating degree hours.

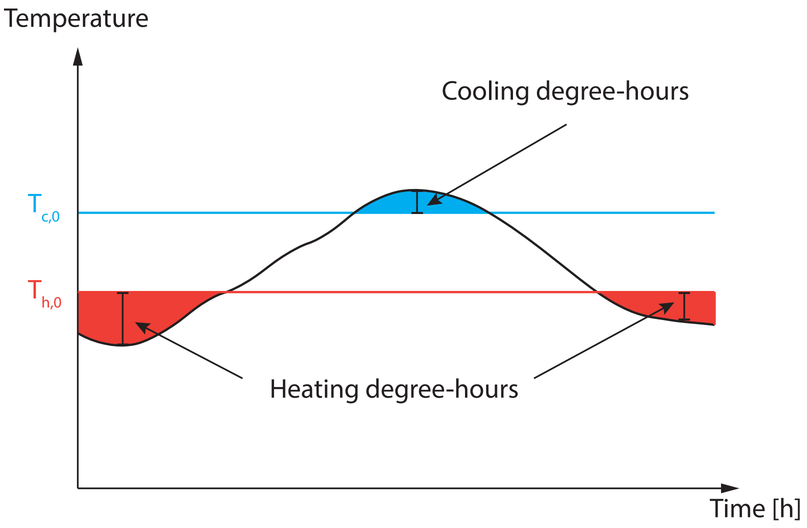


Figure 17: Concept of degree hours

Calculation for k$_{th}$

Details concerning the thermal losses k$_{th}$ are not described in this master thesis. According to the work of two other students for the same project, average thermal losses of 2.22 W/m^{2}K can be considered as a mean value for all buildings [24]. The square meters refers to the energy reference area. In reality, one should evaluates these losses according to the construction plans but since no information was available, a rough estimation as been used for estimating heating and cooling needs.

For the heating demand, the equation can be written as :

$$P_{H,heat,i}\ [W_{heat}/m^2] = k_{th} \cdot \text{Degree-hour}_{h,i} \tag{11}$$

This value represent the heat needed per square meters. Since the heat/cooling are provided by reversible heat pump, the Coefficient of Performance (COP) has to be considered in order to calculate the electricity needs. The COP is defined as the ratio between output power and input power:

$$COP = \frac{\text{Output power}}{\text{Input power}} \left[\frac{\text{kW}_{heat,out}}{\text{kW}_{elec,in}}\right] \tag{12}$$

Therefore the electricity power need is :

$$P_{H,i}\ [W/m^2] = \frac{P_{H,heat,i}}{COP_{heating}} \tag{13}$$

For the cooling demand, the equation can be written as :

$$P_{C,heat,i}\ [W_{heat}/m^2] = k_{th} \cdot \text{Degree-hour}_{c,i} \tag{14}$$

Therefore the electricity power need is :

$$P_{C,i}\ [W/m^2] = \frac{P_{C,heat,i}}{COP_{cooling}} \tag{15}$$

In the literature, the coefficient of performance (COP) for cooling purposes is often defined in energy units as the Energy Efficiency Ratio (EER) [BTU/Wh]. In order to keep coherency in calculation for heating and cooling needs, COP$_{cooling}$ will be used and is defined as :

$$COP_{cooling} = \frac{EER}{3.412} \tag{16}$$

4.1.4 Charging stations

All means of transport on Arkoudi island will be electrical vehicles. Therefore, it is important to estimate the needs for this electrical load.
The total daily consumption of the electric vehicles park is equal to :

$$Cons_{daily} = Nb_{cars} \cdot c \cdot d \tag{17}$$

where

c	Car consumption [kWh/km]
d	Car distance per day [km]
Nb_{cars}	Number of cars

The number of full hours a charger will have to serve is equal to :

$$h_{chargers} = \frac{Cons_{daily}}{P_{chargers} \cdot Nb_{chargers}} \tag{18}$$

where

$h_{chargers}$	Average number of hours a charger is used per day [h]
$Cons_{daily}$	Daily consumption of the EV park [kWh/km]
$P_{chargers}$	Charger power [kW]
$Nb_{chargers}$	Number of chargers

The number of full hours boat chargers will have to serve is calculated in the same way than for cars.

4.1.5 Occupancy

The resort island will be more occupied during the summer season and the weekend. Hence, loads depending on occupancy will vary throughout the year. For example, hotel bedrooms might not be all occupied during the low season. Therefore, a monthly occupancy factor has been defined. The occupancy factor OF$_i$ for each hour i of the year will multiply the load demand at maximum utilization for this hour. When the island is full with the maximum number of persons, the occupancy factor is one. If half of the people is on the island, the occupancy factor is 0.5 .

Some loads are not dependent on the occupancy factor and therefore a binary variable y$_i$ is given for each load whether it will be multiplied by the occupancy factor or not.

4.1.6 Total electricity demand

The total electricity demand for a each load j at a hour i for an occupancy factor of 1 is calculated as follows :

$$P_{i,j} = SF_j \cdot (P_{A,i,j} + P_{L,i,j} + P_{H,i,j} + P_{C,i,j}) \tag{19}$$

where

$P_{i,j}$	Mean hourly power needed at hour i for load j [W]
SF_j	Size factor of load j [m^2 or units]
$P_{A,i,j}$	Appliances demand at hour i for load j [W/m^2 or W/unit]
$P_{L,i,j}$	Lighting demand at hour i for load j [W/m^2]
$P_{H,i,j}$	Heating demand at hour i for load j [W/m^2]
$P_{C,i,j}$	Cooling demand at hour i for load j [W/m^2]

Therefore, the total hourly demand for the entire island is calculated by summing up all the loads, considering where they depend on occupancy or not :

$$P_{i,island} = \sum_{j=1}^{n} Pi,j \cdot (y_j \cdot OF_i) \tag{20}$$

where

$P_i, island$	Total electricity demand at hour i [kW]
$P_{i,j}$	Electricity demand of load j at hour i [kW]
y_i	Binary factor, 1 (0) when the load is (not) dependent on occupancy [-]
OF_i	Occupancy factor at hour i [-]
n	Number of loads

4.2 Electricity supply - Predimensioning

4.2.1 Generators

The design of generators directly depends on the electrical load to be served. The first information that is important is the smallest power load occurring during the year. Since generators optimally run at around 80% of their nominal load, the smallest generator capacity should not be less than :

$$\text{Minimum Generator Power [kW]} = \frac{\text{Minimum load [kW]}}{0.8} \tag{21}$$

Similarly, the sum of all generators running at 80% should not exceed around 115% of maximum load. The 15% accounts for the spinning reserve.

Concerning the size of the other generators, an load analysis should be performed. If a baseload can be noticed, it might be interesting to make a large generator run to serve this load at a higher efficiency than two smaller units. On the other hand, smaller generators can be more flexible and better synchronized in order to optimize their nominal load ratio.

4.2.2 PV panels

Central PV plant with fixed panels

PV central plants are mainly used in locations where there is a lot of sun and where the land does not cost too much. They can go up to hundreds of installed MWp. Here, the goal is to evaluate the potential a central PV plant that would be placed on the island.

There are different ways of predimensioning solar plants, especially in this case study where different energy systems with and without batteries will be compared. HOMER will help to determine the threshold for the economical profitability of solar panels during the optimization.

Central PV plant with tracking

The tracking technology for solar plants becomes interesting for large installations where the economy of scale can have an impact on the total cost. An interesting tracking method is the East-West tracker (Figure 18) which has two main advantages compared to fixed panels. First, it allows to produce more electricity than a fixed panel because it will follow the sun path and harvest more light. The second benefit is the shape of the production curve. Indeed, the electricity production is better distributed during the day. It allows to serve more load in the morning and in the late afternoon while also reducing the peak output power around noon (see Figure 19).

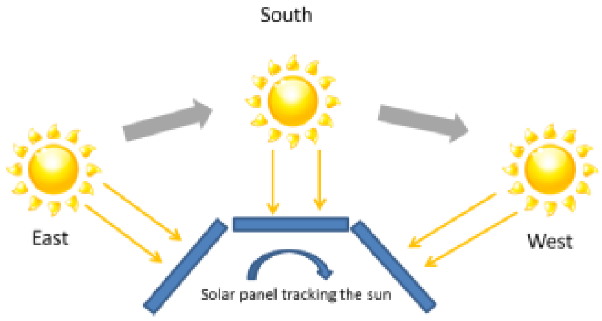


Figure 18: East-West tracker principle [25]

Figure 19 shows the hourly production of 1 kWp that is placed at optimal tilt and 1 kWp with a tracking system. The solar fields have the following properties :

Table 1: Tilt and azimuth information for fixed and tracking plants

	Tilt	Azimuth
Fixed Panels	32° (optimal)	0° (South)
With tracker	Varying	East and West

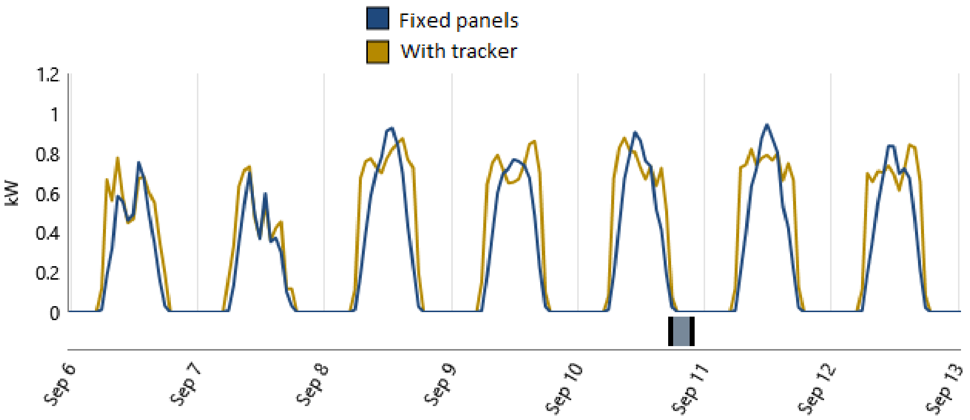


Figure 19: Comparison between the production curves of fixed and tracking panels

Solar energy cost is really low compared with diesel. Its use will be maximized in the HOMER optimization. Assuming fixed panels at optimal tilt and azimuth and a solar plant that can produce 80% of the island peak power at its maximum, the maximum capacity should be around :

$$\text{Maximum Capacity} = \frac{\text{P}_{peak} \cdot 0.8}{\text{Derating factor}} = \frac{2.5MW \cdot 0.8}{0.8} = 2.5 \text{ MWp of solar panels} \tag{22}$$

For the comparison of both fixed and tracking power outputs and economical performances, the same maximum capacity of 2.5 MWp is considered when no batteries are used in the energy system.

4.2.3 Wind turbines

It can be seen in Figure 31, mean wind speed on the west coast of Arkoudi island is about 6.5 m/s. To harvest wind power, the bigger the area, the greater the amount of power the turbine can produce (see Equation 4.2.3). The client has given a maximum unit capacity of 100 kW for the wind turbines in order not to impact too much the landscape.

The theoretical maximum value that can be extracted from wind is :

$$P_{avail} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3 \cdot Cp \tag{23}$$

Where

P_{avail}	Maximum extractable power from wind [kW]
ρ	Air density [kg/m^3]
A	Disk area made by the blades [m^2]
v	Wind speed [m/s]
Cp	Power coefficient (max = Betz value = 0.59) [-]

For the estimation of the levelized cost of electricity, the annual energy production from the wind turbine needs to be estimated. In order to estimate the annual production, the following properties are needed :

- The wind speed distribution
- The wind turbine power curve

Wind speed distribution

A suitable probability distribution for the wind speed can be well represented by the two-parameter Weibull probability density function :

- The scale parameter c
- The shape parameter k

The scale parameter is directly dependent of the average wind speed and the Weibull shape parameter is estimated to be equal to 2, which is a common value for a wind speed distribution [3].

The excel function "Weibull.dist" has been used in order to calculate the wind speed distribution shown in Figure 20. the function uses the weibull probability function :

$$f(x;\alpha;\beta) = \frac{\alpha}{\beta^{\alpha}} \cdot x^{\alpha-1} \cdot e^{-(x/\beta)^{\alpha}} \tag{24}$$

with

$$\alpha = \text{shape parameter k} = 2 \tag{25}$$

and

$$\beta = \frac{\text{avg wind speed}}{e^{Ln(\Gamma(1+1/k)}} \tag{26}$$

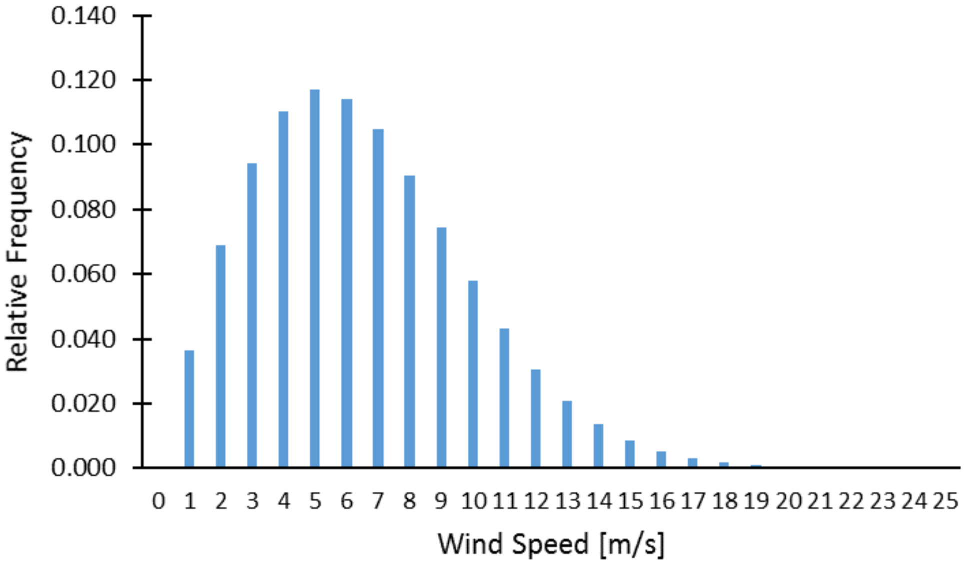


Figure 20: Weibull distribution of wind speed.

Wind turbine power curve

All wind turbines have their own power curve given in their data sheet. This curve gives how much power the wind turbine extracts depending on wind speed. This value depends on the turbine characteristics. When the wind is too low, the turbine will not start turning and therefore output power is 0. The cut-in wind speed is the wind speed for which the turbine will start producing power. In the same way, too much wind could damage the turbine therefore the cut-off speed is the maximum speed at which the turbine will operate. Above this limit, the turbine will be stopped. The wind power curve of a 100 kW wind turbine is given in Figure 21.

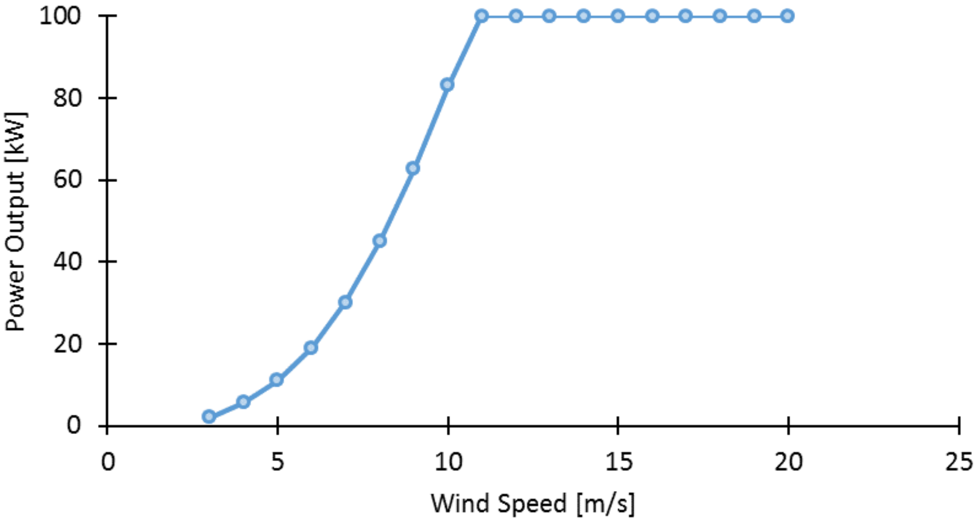


Figure 21: Power curve of the wind turbine XANT M-21 100kW

The overall losses for wake, tip and drag losses can be estimated to around 30% [26]. By multiplying the number of hours of each wind speed with the respective power output from the wind turbine, the annual energy production would be around 295,000 kWh for the 100 kW turbine. The capacity factor is equal to :

$$CF_{wind} = \frac{\text{Energy produced}}{\text{Nominal power} \cdot 8760h} = \frac{295,443}{876,000} = 23.6\ \% \tag{27}$$

Table 2: Annual energy produced at each wind speed.

Wind Speed (m/s)	Probability	Hours/year	Power curve (kW)	Energy (kWh/year)
0	0.000	0	0	0
1	0.036	320	0	0
2	0.069	605	0	0
3	0.094	827	2	1,653
4	0.110	968	5.6	5,418
5	0.117	1,023	11	11,255
6	0.114	1,001	19	19,014
7	0.105	917	30.1	27,598
8	0.091	793	45	35,679
9	0.074	650	62.6	40,708
10	0.058	508	83.1	42,177
11	0.043	378	100	37,786
12	0.031	269	100	26,880
13	0.021	183	100	18,296
14	0.014	119	100	11,928
15	0.009	75	100	7,454
16	0.005	45	100	4,469
17	0.003	26	100	2,571
18	0.002	14	100	1,420
19	0.001	8	100	754
20	0.000	4	100	384
21	0.000	2	0	0
22	0.000	1	0	0
23	0.000	0	0	0
24	0.000	0	0	0
25	0.000	0	0	0

4.2.4 Battery storage

Batteries can either be used for stability only or for stability and storage. In the first case, they are designed to cover the sudden power changes in the renewable production. For example, the PV output can drastically decrease in case of shading on the panels.

For stability and storage purposes, an economical optimization can be performed to know how much battery capacity should installed. Sometimes, the requirement in terms of number of hours (or days) of autonomy can be used, especially in case where there is no backup technology that could serve the load if the battery bank is empty.

Batteries for stability only

The power of the battery bank needs to cover the power intermittency of the renewable energy resources. It is assumed that the maximum power change of PV panels is about 80% of its maximum output. The power output a battery bank can serve depends on the C-rate. In describing batteries, discharge current is often expressed as a C-rate in order to normalize against battery capacity, which is often very different between batteries. The C-rate is a measure of the rate at which a battery is discharged relative to its maximum capacity. A 1C rate means that the discharge current will discharge the entire battery in 1 hour. A 2C rate means that the discharge current will be twice the discharge current at 1C [27].

Since the battery should be should for stability only, the maximum depth of discharge (DoD) has been considered to be 10%. Considering a battery that can be delivered a rate of 2C for several minutes, the required capacity when installing tracking PV of 2.5 MWp is roughly estimated to :

$$\text{Required capacity} = \frac{P_{PV,max} \cdot 0.8}{2} = 1,000 \text{ kWh} \tag{28}$$

Batteries for stability and storage

In this configuration, the battery bank is also used to store energy. In case of a required number of days of autonomy, the needed capacity can be calculated by making sure the battery bank can serve the load. This is particularly the case for autonomous energy system. Here, generators will be used as backup and for peak loads, therefore, only an optimization can correctly estimate the needed capacity of the battery bank.

4.3 Electricity supply - Optimization

4.3.1 Technical calculations

Generators

In HOMER, the user defines the fuel consumption in liter per hour (L/h) of the chosen generator. Often, companies give values of fuel consumption at different percentage of nominal power (50%, 75%, 100%, 110%), for which HOMER estimates a fuel curve.

In HOMER the generator's electrical efficiency is defined as the electrical energy coming out divided by the chemical energy of the fuel going in. The following equation gives this relationship:

$$\eta_{gen} = \frac{3.6 \cdot P_{gen}}{\dot{m}_{fuel} \cdot LHV_{fuel}} \tag{29}$$

where

P_{gen}	Electrical output [kW]
$\dot{m}_{fuel}$	Mass flow rate of the fuel [kg/h]
LHV_{fuel}	Lower heating value of the fuel [MJ/kg]
3.6	unit factor because 1kWh = 3.6 MJ

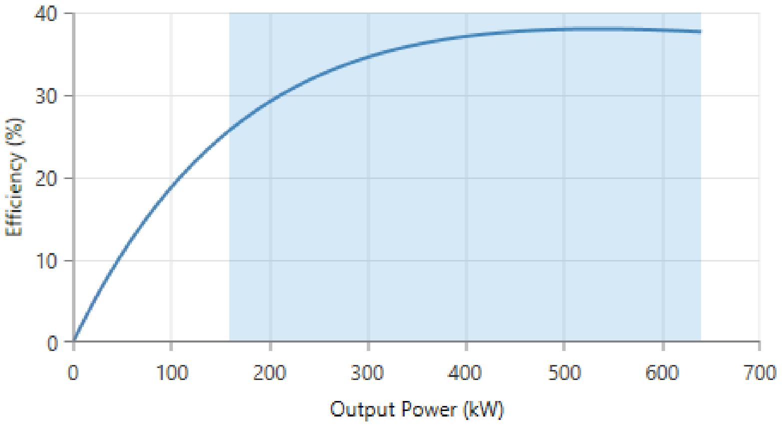


Figure 22: Example of a generator efficiency curve

Knowing the efficiency curve and how it links the power output with the mass flow rate, HOMER can estimate the fuel consumption of each hour depending on how much power a generator will have to produce.

PV Panels power output

HOMER uses the following equation to calculated the PV panels power output :

$$P_{PV} = Y_{PV} f_{PV} \left(\frac{G_T}{G_{T,STC}} \right) [1 + \alpha_P (T_c - T_{c,STC})] \tag{30}$$

where

Y_{PV}	rated capacity of the PV array [kW]
f_{PV}	PV derating factor [%] (chosen at 85 %)
G_T	solar radiation incident on the PV array [kW/m^2]
$G_{t,STC}$	incident radiation at standard test cond. [1kW/m^2]
α_P	temperature coefficient of power [%/°C]
T_c	PV cell temperature [°C]
$T_{c,STC}$	PV cell temperature at standard test cond. [25°C]

The PV central plant with fixed panels is simulated assuming a optimal tilt and azimuth in terms of electricity production. They are assumed to be tilted at 32° and to be facing south. Details concerning the calculation of the cell temperature are not described here but can be found in the HOMER help manual. The higher the temperature of the cell, the lower the efficiency. Temperature losses are not negligible especially in hot environments.

The panel efficiency represents how much of the solar irradiation can be converted into electricity. This efficiency reveals the performance of the panel because it is giving how many kW of electricity can be produced from 1 kW of light. The efficiency can be calculated as follows :

$$\eta_{STC} = \frac{Y_{PV}}{A_{PV} \cdot G_{T,STC}} \tag{31}$$

Where

η_{STC}	efficiency of the PV module under standard test conditions [%]
A_{PV}	surface area of the PV module [m^2]
Y_{PV}	rated capacity of the PV array [kW]
$G_{T,STC}$	radiation at standard test conditions [1 kW/m^2]

For a standard panel with a peak power of 300Wp and an area of 1.6 m^2, the efficiency is :

$$\eta_{STC} = \frac{0.3 \text{ kWp}}{1.6m^2 \cdot 1kW/m^2} = 18.75\% \tag{32}$$

Tracking system

HOMER does not directly allow the single axis tracking with the pivoting axis north-south oriented with the panels that faces East in the morning and West in the afternoon.

Nevertheless, it is possible to model this situation in HOMER by setting the PV tracking system to "Horizontal axis, continuous adjustment" and the azimuth to 90°. It allows to correctly calculate azimuth and slope angles as shown in Figure 23.

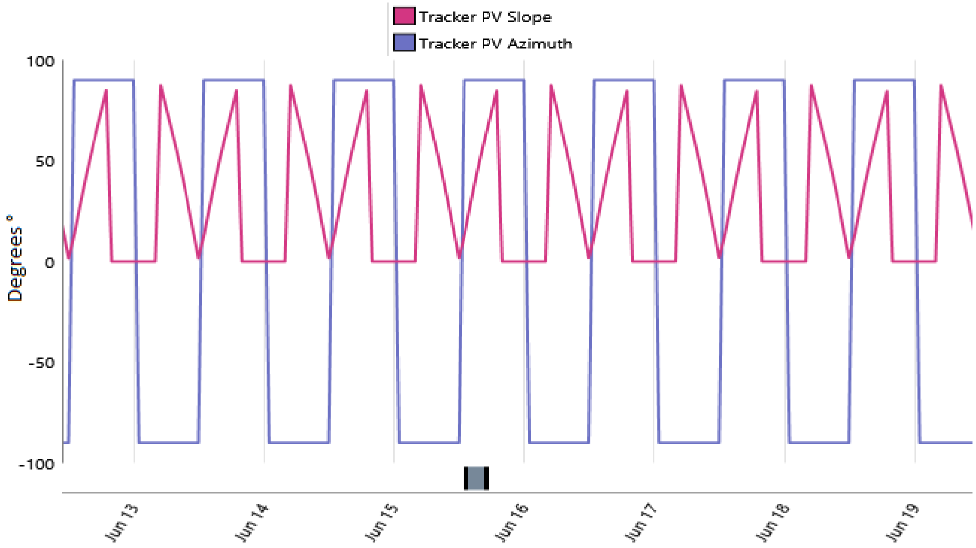


Figure 23: Azimuth and slope of PV panels for the tracking technology

Wind turbines power output

HOMER calculates the power output of the wind turbine in each time step. This requires a three-step process to first calculate the wind speed at the hub height of the wind turbine, then to calculate how much power the wind turbine would produce at that wind speed at standard air density, then to adjust that power output value for the actual air density.

Using the wind resource input in the software, HOMER calculates the wind speed at the hub height of the wind turbine with the following logarithmic equation :

$$U_{hub} = U_{anem} \cdot \frac{ln(z_{hub}/z_0)}{ln(z_{anem}/z_0)} \tag{33}$$

where

U_{hub}	Wind speed at the hub height of the wind turbine [m/s]
U_{anem}	Wind speed at anemometer height [m/s]
z_{hub}	Hub height of the wind turbine [m]
z_0	Anemometer height [m]
z_{anem}	Surface roughness length [m] (=0.1m for rough pasture)

Once HOMER has determined the hub height wind speed, it refers to the wind turbine's power curve to calculate the power output one would expect from that wind turbine at that wind speed under standard conditions of temperature and pressure. Figure 24 gives an example of a power curve that is used to estimate the output power of the wind turbine.

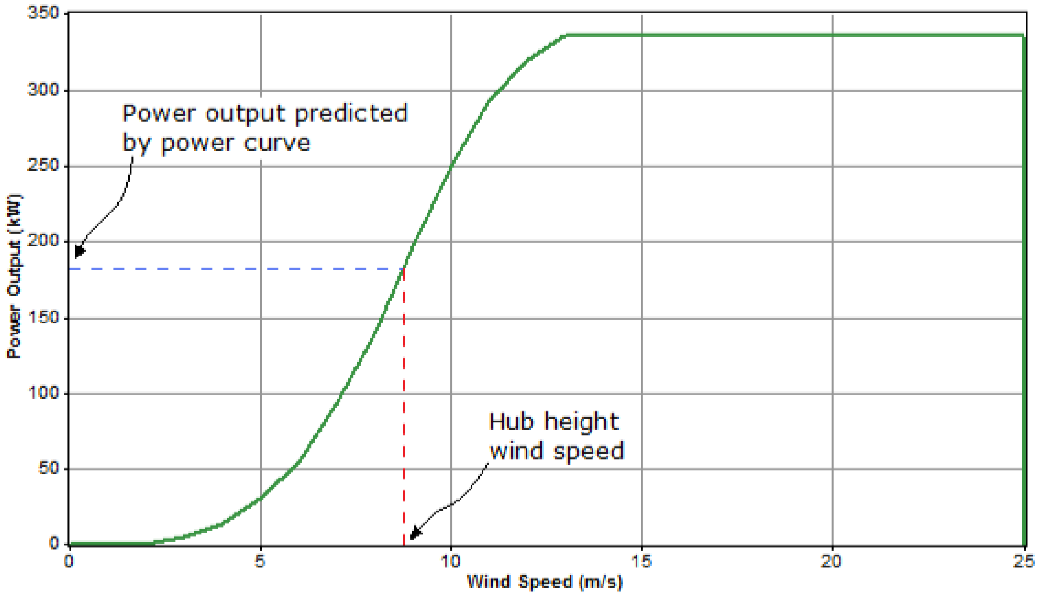


Figure 24: Important information on the power curve graph of a wind turbine.

The ouptut power can be derated by a loss factor which account for several different factor such as availability, drag loss, tip loss, etc.

Finally the power output for the standard air density is adjusted to actual conditions. HOMER multiplies the power value predicted by the power curve by the air density ratio, according to the following equation :

$$P_{WTG} = \left(\frac{\rho}{\rho_0}\right) \cdot P_{WTG,STP} \tag{34}$$

P_{WTG}	Wind turbine power output [kW]
$P_{WTG,STP}$	Wind turbine power output at standard temperature and pressure [kW]
ρ	Actual air density [kg/m^3]
ρ_0	Air density at standard temperature and pressure (1.225 kg/m^3)

Battery Storage

The battery calculation details can be found in the HOMER manual. For the sake of the thesis, the generic 1 kWh of the Li-Ion [ASM] has been used and optimized by considering a certain number of this cell. This battery uses the modified kinetic battery model defined by HOMER. The battery has the following properties :

Table 3: Battery properties.

Nominal voltage (V)	3.7
Nominal Capacity (kWh)	1.02
Maximum Capacity (Ah)	276
Capacity Ratio	1
Rate Constant (1/hr)	1
Effective Series Resistance (ohms)	0.00036
Other round-trip losses (%)	8
Fixed bulk temperature C	20
Maximum Charge current (A)	270
Maximum Discharge Current (A)	810

For the end of life of the battery bank, it is considered dead and instantly replaced when either the time-and-temperature degradation variable or the cycle degradation variable reaches the fraction specified by the capacity degradation limit input. This parameter has been set to 15% because this was leading to a battery lifetime of around 7.5 years. Renemig's experience in the domain has considered it as a consistent lifetime.

Excess electricity

The excess electricity is the total amount of excess electricity that occurs throughout the year. When the production cannot be served or stored, it is accounted as excess electricity.

4.3.2 Economical calculations

Real discount rate

The real discount rate is accounting not only for the value of money but considers inflation too. Its formula is given by the Fisher equation and reads :

$$i = \frac{1 + i_{nom}}{1 + f} - 1 = 5.9\% \tag{35}$$

where

i	Real discount rate [-]
i_{nom}	Nominal discount rate [-]
f	inflation rate [-]

Net Present Cost (NPC)

The net present cost is the total cost of a project over its lifetime, annualized at the present year. It is calculated as follows :

$$\sum_{t=0}^{n} \frac{I_t + O\&M_t + Rep_t - S_t}{(1+i)^t} \tag{36}$$

where

I_t	Investment cost at year t [\$]
$O\&M_t$	Operating and Maintenance cost at year t [\$]
Rep_t	Replacement cost at year t [\$]
S_t	Salvage value (only at the end of the project) [\$]
i	Real discount rate [-]
n	Project lifetime [years]

Net Present Value (NPV)

The concept of net present value is mainly used in projects where investments create revenues. Its purpose is to evaluate whether the investment will generate more revenues than the investment, taking into account the time value of money. The main difference with the net present cost is this concept of generating revenues.

$$\sum_{t=0}^{n} \frac{R_t - C_t}{(1+i)^t} \tag{37}$$

where

R_t	Revenues at year t [$]
C_t	Costs at year t [$]
i	Real discount rate [-]
n	Project lifetime [years]

Levelized cost of Energy (LCOE or COE)

The levelized cost of energy is a economical measure of a power source that allows comparison of different methods of electricity generation on a consistent basis. It is an economic assessment of the average total cost to build and operate a power-generating asset over its lifetime divided by the total energy output of the asset over that lifetime. The LCOE can also be regarded as the average minimum price at which electricity must be sold in order to break-even over the lifetime of the project [28].

The LCOE ($/kWh) of an entire system is calculated as follows :

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + O\&M_t + R_t - S_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_{served,t}}{(1+i)^t}} \tag{38}$$

where

I_t	Investment cost at year t [$]
$O\&M_t$	Operating and Maintenance cost at year t [$]
R_t	Replacement cost at year t [$]
S_t	Salvage value (only at the end of the project) [$]
i	Real discount rate [-]
n	Project lifetime [years]
$E_{served,t}$	Served electricity at year t [kWh]

Salvage Value

The salvage value is a cash flow that occurs at the end of the project lifetime. It accounts for the remaining value of the system components. It accounts for the fact that a newly replaced components could be sold or still used at the end of the project's lifetime. HOMER assumes a linear depreciation from the replacement cost until the end of the component's lifetime. For example, consider a project's lifetime of 25 years, a wind turbine cost of $100,000 and a lifetime of 15 years. The latter has to be replaced at year 15 and will be used for 10 years until the end of the project. Its salvage value will be :

$$\text{S} = \$100,000 \cdot (5/15) = \$33,333 \tag{39}$$

4.3.3 Environmental calculations

Renewable fraction

The renewable fraction is the fraction of the energy delivered to the load that originated from renewable power sources. HOMER calculates the renewable fraction using the following equation:

$$f_{ren} = 1 - \frac{E_{nonren} + H_{nonren}}{E_{served} + H_{served}} \tag{40}$$

where

E_{nonren}	Nonrenewable electrical production [kWh/yr]
H_{nonren}	Nonrenewable thermal production [kWh/yr]
E_{served}	Total electrical load served [kWh/yr]
H_{served}	Total thermal load served [kWh/yr]

Since no thermal load will be modeled in this master thesis, the renewable fraction is simplified to :

$$f_{ren} = 1 - \frac{E_{nonren}}{E_{served}} \tag{41}$$

CO_2 emissions

Details for CO_2 emissions calculation are given in subsection 7.2.

5 Data

5.1 Electricity demand

5.1.1 Environmental and climate data analysis

Before estimating any energy consumption and any power generation system, it is important to have a good understanding on the case study's environment and climate. Indeed, factors such as mean temperature, max and min temperature, daylight time, natural resources availability, topography and geographical situation may have a significant impact on how the people behave and therefore consume throughout the year. It can also determine which power generating technologies will have the most economical performance and technical feasibility.

Arkoudi is a small Greek island situated in the Ionian Sea, 5 kilometres south of Lefkada. It is a private island and has no residential inhabitants but is administrated by the municipality of Ithaca.

Accessible by boat, the island could be supplied from Lefkada island which is linked to the country with a terrestrial connection. As it can be seen in Figure 1, Arkoudi island is very green and has no apparent inhabitable region.

There is a Mediterranean climate which is characterized by humid winters coupled with dry and hot summers (Figure 25). This will be an important parameter when estimating heating/cooling demand.

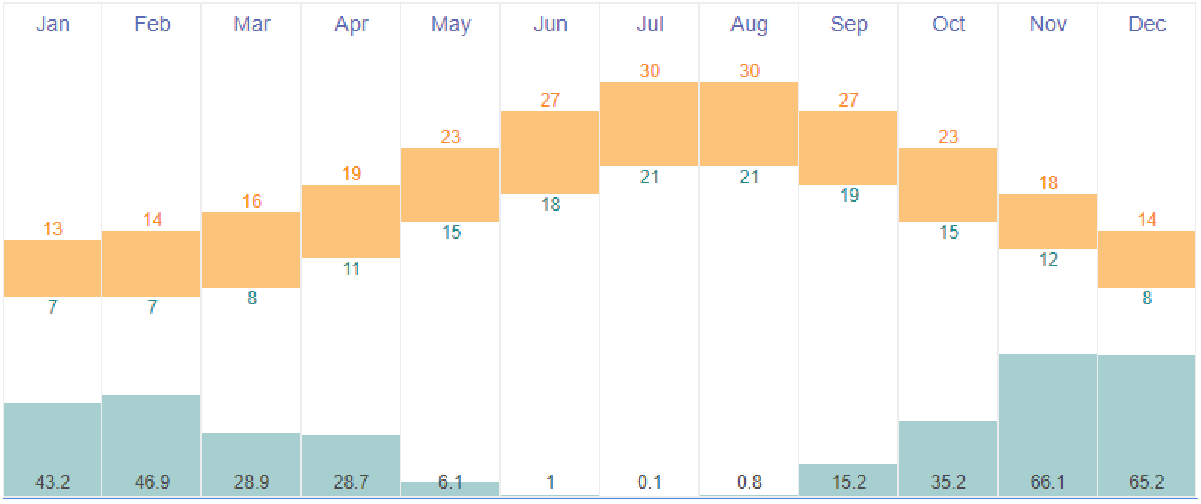


Figure 25: Annual weather averages on Arkoudi island [29]

5.1.2 Inputs

Inputs from the client concerning the electricity demand are the following :

- Type of buildings + their area
- Number of guests that can come on the island
- Number of staff member who will work on the island
- Type of heating system (reversible heat pumps)
- Type of vehicles (electric)

5.1.3 Appliances

The information needed to estimate the appliances electricity consumption are :

- Hourly mean power $P_{a,mean}$ at full utilization [W/m^2]
- Utilization daily profile [-]

The hourly mean power has been estimated with the help of Renemig experience in the domain of electrical loads assessment. For the utilization profiles, the Swiss norm SIA 2024 and the common sense have helped determining the hourly profiles for each type of local. Values used in the calculations are shown in Appendix A.

5.1.4 Lighting

Lighting characteristics for the representative locals have been estimated mainly thanks to the Swiss norm SIA 380/4. For sport illumination requirement, the European norm have been considered [30]. Values used in the calculations are shown in Appendix B.

5.1.5 Heating and cooling

In order to take into account the hourly profile of heating and cooling, the hourly temperature needed to be evaluated. We will simplify the methodology by considering monthly averages and a daily temperature profile.

Table 4: Monthly temperature on Arkoudi island [29]

	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Min	7	7	8	11	15	18	21	21	19	15	12	8
Mean	10	10.5	12	15	19	23	25	26	23.5	19.5	15.5	11
Max	13	14	16	19	23	27	30	30	27	23	18	14
(Max - Min)	6	7	8	8	8	9	9	9	8	8	6	6

As it can be seen on Table 4, the difference between the minimum temperature and the maximum temperature varies from 6 to 9 degrees. An average difference value of 8 degrees and a typical day are assumed to estimate the temperature profile below :

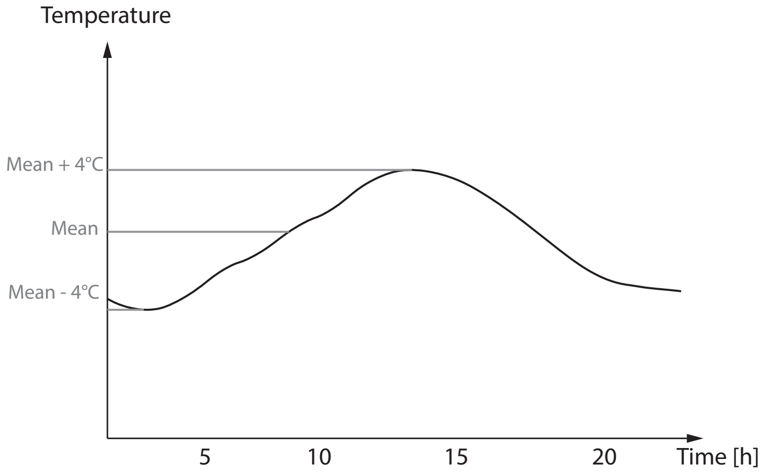


Figure 26: Average temperature profile

The profile in Figure 26 will be applied for each day of each month. Therefore, the estimated hourly temperature on Arkoudi island is estimated and the calculation to get the degree-hour at each hour can be performed.

Figure 27 shows the heating and cooling degree-hours estimation for all months on Arkoudi island. These values are used in order to calculate the demand for heating/cooling on a hourly basis.

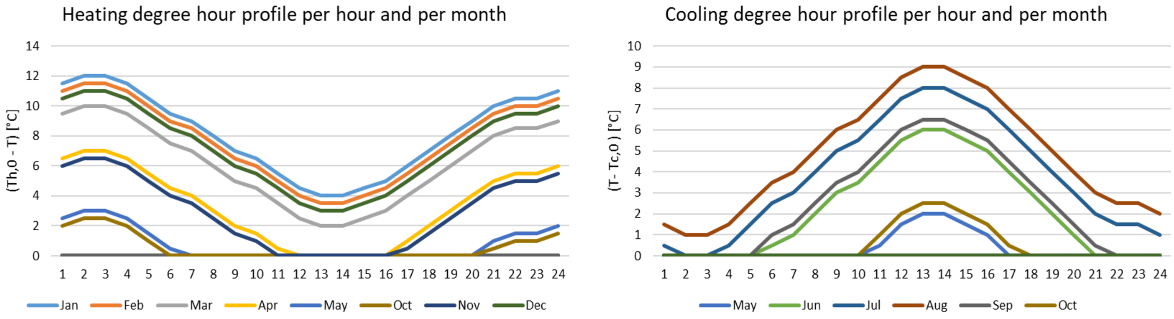


Figure 27: Degree hours estimated for heating and cooling, for each hour of the year.

The coefficient of performance of the reversible heat pumps have assumed to be 4 for heating and 3.5 for cooling.

5.1.6 Charging stations

The average consumption of an electric car is between 15 to 20 kWh/100km [31]. Assuming only small drive distances and therefore lower efficiency, the upper value of 20kWh/100km is considered. The following assumptions are made :

- 1 car for 2 people on the island (guests and staff).
- 1 car is driven around is driven 20km per day
- The battery capacity is 30 kWh

Total daily consumption is equal to :

$$Cons_{daily} = Nb_{cars} \cdot c \cdot d \tag{42}$$

According to how many chargers should be installed in different locations, an estimation of around 95 car chargers need to be installed on the island. Each charger has a power of 11kW. The number of full hours a charger will have to serve is equal to :

$$h_{chargers} = \frac{Cons_{daily}}{P_{chargers} \cdot Nb_{chargers}} = \frac{1840kWh/day}{11kW \cdot 95} = 1.76 \approx 2 \text{ full hours per day.} \tag{43}$$

For the boat charging stations, the client would like to install 10 chargers of 50kW and the following assumptions holds :

- Boats should be able to travel four tours of the island (4x15 km) per day
- Boat consumption is around 1.9 kWh/km [32]
- There will be 15 boats

The number of full hours a boat charger will have to serve is calculated in the same way than for cars.

5.1.7 Occupancy

The resort island will be more occupied during the summer season and the weekend. Hence, loads depending on occupancy will vary throughout the year. For example, hotel bedrooms might not be all occupied during the low season. Therefore, a monthly occupancy factor has been defined. Moreover, it is assumed that the weekly consumption will be 20% smaller than during the weekend. The monthly occupancy is defined as follows :

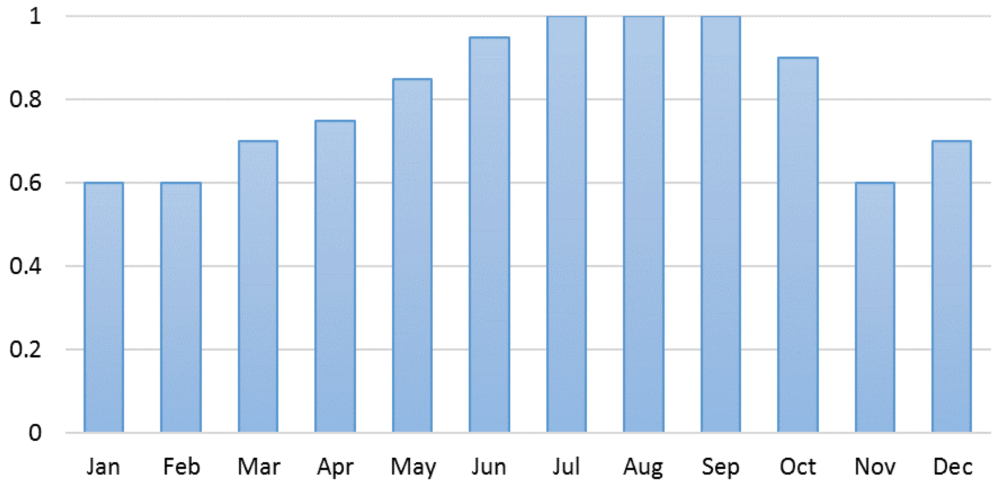


Figure 28: Monthly occupancy as fraction of maximum people on the island

Weekends have a additional factor of 1 while weekdays have a additional factor of 0.8. For example, the occupancy factor for a Tuesday in May will be :

$$\mathrm{OF} = 0.85 \cdot 0.8 = 0.68 \tag{44}$$

The electricity demand of occupancy-related loads will therefore be 32% less than for the same hour where the occupancy is one (example : weekends in July).

5.2 Electricity supply

5.2.1 Technology potential and constraints

Photovoltaic Panels

The economical profitability of the photovoltaic panels is not the same around the world. Indeed, one panel will produce more electricity where annual irradiance is greater, while investment cost will remain the same. On Arkoudi island, irradiance is around 40% higher than in Switzerland (Figure 29) and makes the solar panels even more competitive compared to traditional technologies such as diesel generators.

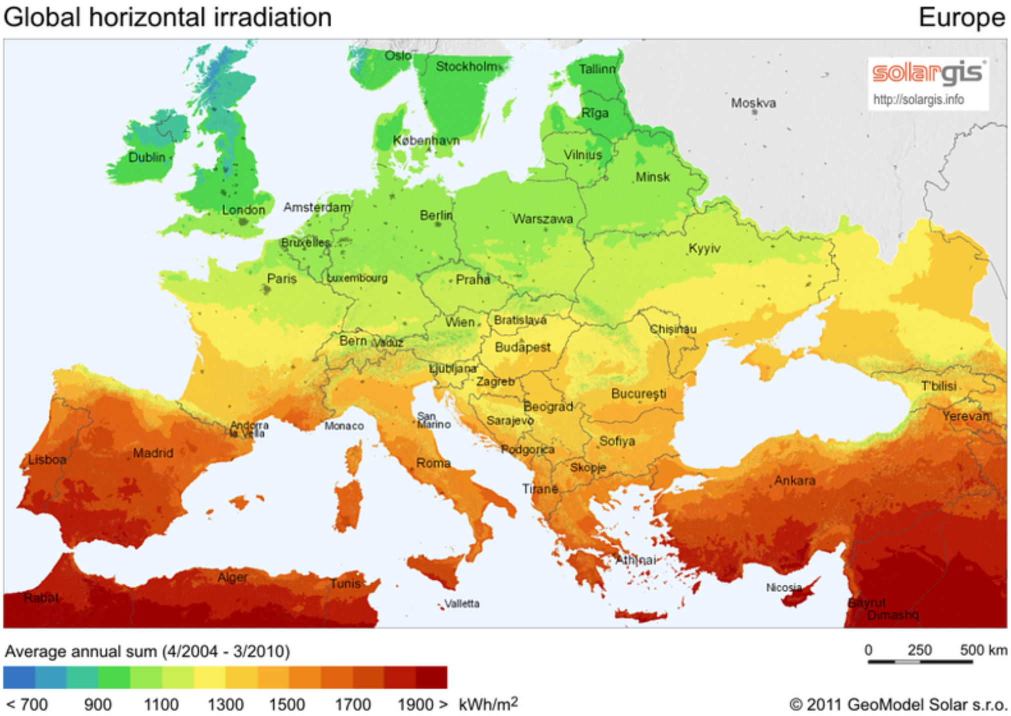


Figure 29: Solar irradiance map [33].

Lausanne (CH)	Arkoudi (GR)
1,300 kWh/m^2	1,800 kWh/m^2

The maximum central capacity that can be installed depends on the island area dedicated to the solar plant. The client has not given any information about this figure but it is assumed that a maximum of 2% of the entire island is covered by a central plant. It is known from Renemig experience that a capacity of around 1MWp can be installed on 1 ha (or 100MWp/km^2).

$$\text{Max Capacity} = 0.02 \cdot 4.25\ km^2 \cdot 100\ MWp/km^2 = 8.5\ MWp \tag{45}$$

Figure 30: Representation of the maximum solar capacity compared to the island area.

Wind Turbines

The wind potential on Arkoudi island is not the best in the region but can still help increasing the renewable share in the energy system with a economically viable cost. The mean wind speed is 6.5 m/s on the west coast at 50m height.

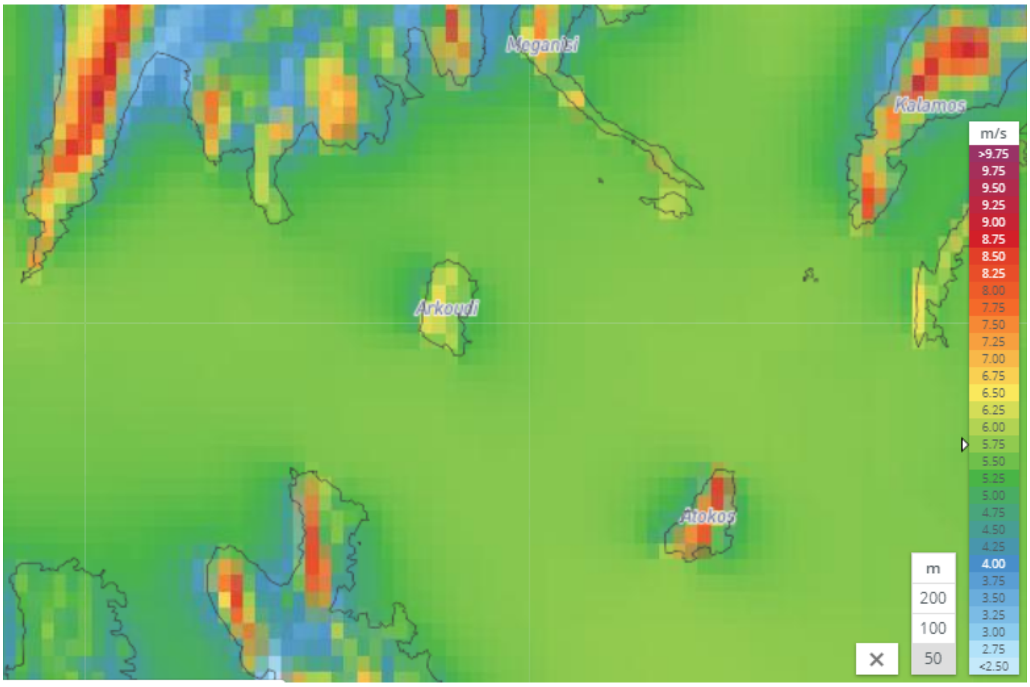


Figure 31: Average mean speed for on Arkoudi island [35].

The client has given a maximum power output of 100 kW per turbine. Considering a distance of around 100 meters between turbines and a implementation on the highest point of the west coast, a total number of 20 turbines is taken as maximum. The points at the top of Arkoudi island are not taken as implementation possibilities because it will be the location of the main port where all the guests will be arriving. Moreover, it is the closest part to the mainland, which would make the turbine implementation affecting the landscape.

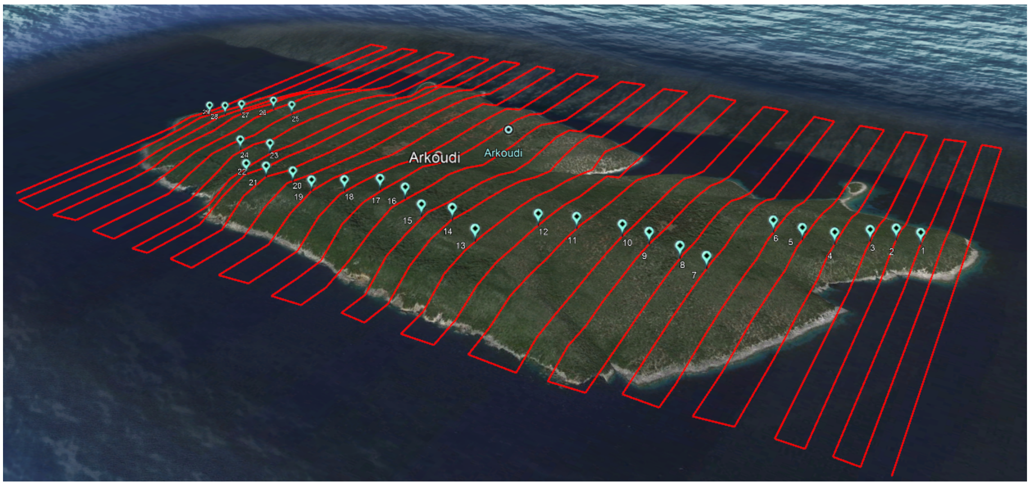


Figure 32: Highest points, subjected to wind turbine implementation.

Biomass
Biomass potential on Arkoudi island is unfortunately not sufficient in order to deploy all the infrastructure to harvest wood. According to Renemig company, the forest on Arkoudi island (which is mainly made of shrubs rather than high trees) could only generate around 0.2 kg per m^2 per year. Even assuming the harvest of 80% of the island area, the annual collected wood would only reach around 680 tons. Deducing the wood needed for other applications such as construction and the use in chimneys, the remaining resource is too low to justify the development of the biomass infrastructure.

5.2.2 Economical data

The economical figures have been obtained from the practical experience of Renemig Company, assuming the project would start in the coming five to ten years. They know the Greek market and this makes their estimation better than estimating a value with different studies. The following table summarizes the costs considered for the energy system optimization.

The values shown in Table 5 already consider the economy of scale obtained by the large installation capacities occurring in this master thesis. This explains also the higher cost for distributed PV than for a central plant due to the multiple deployments needed to install panels on different roofs. Moreover, there should be a inverter a each production point while the inverter design could be better optimized for a central plant.

Table 5: Economical values used in the optimizations.

Technology	**Investment**	**O&M**	**Replacement**	**Lifetime**
Generators	250 \$/kW	0.05 \$/kW/h	187.5 \$/kW	40,000 h
PV central fixed	800 \$/kWp	20 \$/kWp/yr	150 \$/kWp	25 years
PV central tracking	900 \$/kWp	30 \$/kWp/yr	200 \$/kWp	25 years
PV distributed	1000 \$/kWp	20 \$/kWp/yr	150 \$/kWp	25 years
Battery storage	300 \$/kWh	3 \$/kWh/yr	250 \$/kWh	7.5 years
Wind turbine	3000 \$/kW	50 \$/kW/yr	2500 \$/kW	15 years
Converter	300 \$/kW	0 \$/kW/yr	300 \$/kW	15 years

Levelized cost of electricity

The levelized cost of electricity depends on four main factors, namely the costs linked to the technology, its energy production (or the energy served), its lifetime and the discount rate. Moreover, one should notice that the temporality of the production and the costs affects the net present cost.

An example of the calculation is performed here below for a generator, a central plant of fixed panels as well as a battery bank storage to also show how they differ in their operation.

It is assumed that the generator has a nominal capacity of 640 kW and a lifetime of 40,000h. It runs 4000 hours per year and therefore can be used during 10 years. It runs at its best efficiency at 500 kW, where 135L/hr of fuel are burned. Its investment cost is 160,000 and it has a operation and maintenance cost of 32$/hr. The following table resumes its operation and cashflows.

	0	**1**	**2**	**⟶**	**9**	**10**
Investment	-160,000					
Fuel		729,000	729,000	...	729,000	729,000
O&M		128,000	128,000	...	128,000	128,000
Total costs	-160,000	857,000	857,000	...	857,000	857,000
Energy produced		2,000,000	2,000,000	...	2,000,000	2,000,000

The real discount rate is supposed to be 5.9 %, therefore the LCOE is equal to :

$$LCOE_{Gen} = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+i)^t}}{\sum_{t=0}^{n} \frac{E_{produced,t}}{(1+i)^t}} = 0.418\$/\text{kWh} \tag{46}$$

For PV panels, a electricity production of around 1.6 kWh per Wp can be achieved on Arkoudi island [34]. A conservative lifetime of 25 years is considered for the panels. Operation and Maintenance (O&M) is 20$ per year and kWp and investment is 800 $ per kWp.

$$LCOE_{PV} = \frac{\sum_{t=1}^{25} \frac{20[\$/kWp]}{(1+0.059)^t} + 800[\$/kW]}{\sum_{t=1}^{25} \frac{1,679[kWh/kWp]}{(1+0.059)^t}} = 0.049\ \$/\text{kWh} \tag{47}$$

In reality, panels decrease in performance and will loose 20% in production at year 25. This has not been taken into account here because the simulation time in HOMER will increase exponentially when considering multi-year values. However, panels can last more than 25 years in reality. Assuming a real lifetime of 35 year and an linear decrease in performance, the LCOE is equal to 0.051 which is very similar to the one considering a conservative lifetime and no production depreciation.

The economical profitability of a battery bank will directly depend on the storage wear cost of the battery. The storage wear cost is the cost of cycling energy through the storage bank. Each kWh of throughput brings the storage bank that much closer to needing replacement. HOMER calculates the storage wear cost using the following equation [3] :

$$c_{bw} = \frac{C_{rep,batt}}{N_{batt} \cdot Q_{lifetime} \cdot \sqrt{\eta_{rt}}} \tag{48}$$

Where

c_{bW}	Battery wear cost [\$/kWh]
$C_{rep,batt}$	replacement cost of the storage bank [\$]
N_{batt}	the number of batteries in the storage bank
$Q_{lifetime}$	lifetime throughput of a single storage [kWh]
η_{rt}	storage roundtrip efficiency [-]

However, this value does not consider investment cost and therefore does not properly define the cost of using batteries. The equation above gives the cost of storing electricity in a situation where the battery bank is installed and only needs battery replacements. Moreover, the value of money is not considered in this equation.

Instead, the levelized cost of storing electricity should be calculated in the same way than for other technologies. The difference is that the energy that is stored in the battery directly depends on the excess electricity from other technologies and the use of the battery bank.

In the best case scenario where the lifetime in terms of energy throughput is reached before replacement, and considering a lithium-ion battery with a lifetime of 2500 cycles at a DOD of 50%, 1 kWh installed could store 2500kWh. Assuming a investment cost of 300\$/kWh, a replacement cost of 250 \$/kWh every 7.5 years and a maintenance cost of 3\$/kWh, the levelized cost of storage (LCOS) would be :

$$LCOS = \frac{\sum_{t=1}^{8} \frac{3[\$/kWh]}{(1+0.059)^t} + 300[\$/kWh]}{\sum_{t=1}^{8} \frac{312.5kWh}{(1+0.059)^t}} = 0.18 \text{ \$/kWh} \tag{49}$$

There can be some challenges to express the levelized cost of stored electricity in a single measure since it depends on the use of the storage in terms of throughput but also in terms of temporality. Here, a estimation of the LCOS is given in a scenario where there is a very good use of the battery capacity.

The real battery storage cost will therefore depend on each case and needs to be calculated for each strategy. The economical feasibility of the battery needs a simulation to estimate how much electricity can really flow in the storage bank. In that sense, HOMER is a good tool to evaluate the economical feasibility of the battery storage.

The cost of producing electricity and storing it in the batteries is :

$$\text{Generation cost} = \text{storage cost} + \text{energy cost} \tag{50}$$

Since the batteries are charged with excess electricity that would have been lost otherwise, the energy cost can be considered as zero.

5.2.3 Environmental data

The last data category is the environmental data. They are useful in order to calculate several technology power outputs as well as estimating the electricity demand.

Solar irradiance has been directly downloaded from HOMER which uses the NASA Surface meteorology and solar energy database. The values for each month can be found in Figure 33.

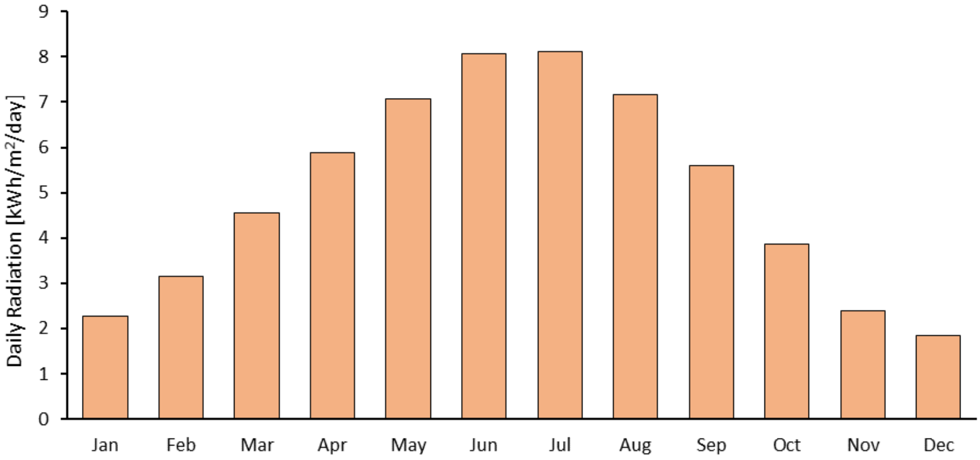


Figure 33: Monthly average irradiance on Arkoudi island

The wind resources data have been downloaded from the same database but scaled to the average wind data estimated thanks to the Figure 31, which shows that the average wind speed on the west coast is about 6.5 m/s.

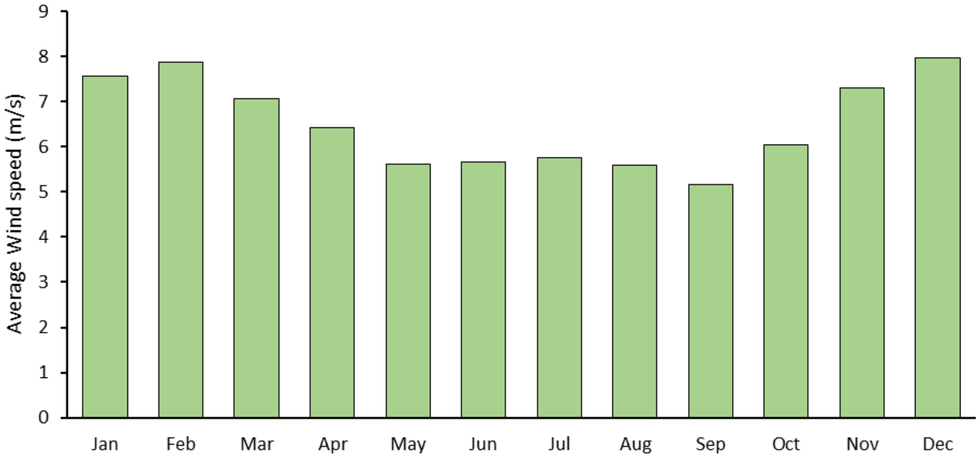


Figure 34: Monthly average wind speed on Arkoudi island at 50m height [36]

For temperature resources data, they have been already mentioned in this master thesis and can be found in subsubsection 5.1.5.

5.2.4 Simulation data

The HOMER software is often used to model microgrids but needs to be well managed in order to simulate systems that reflect reality. The base parameters for simulations need to be relevant and coherent. Economical assumptions used for the simulations are listed below :

- Nominal discount rate = 8%
- Excepted inflation = 2%
- Project lifetime = 25 years

- Operating reserve for generators = 15% of current load
- Optimization on a hourly basis

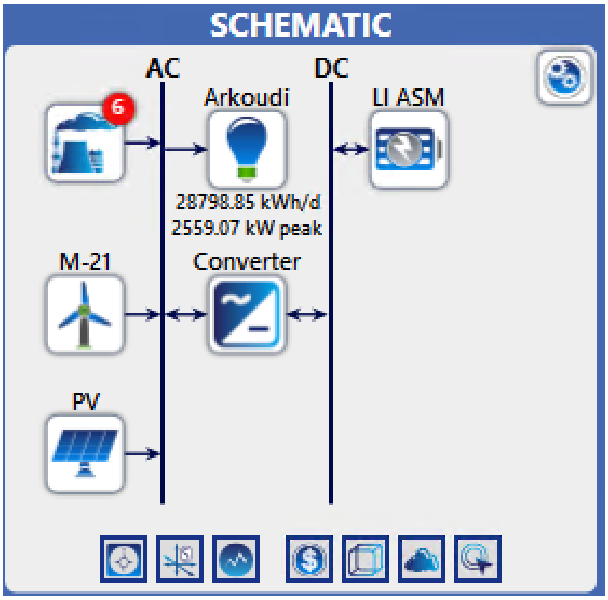


Figure 35: Schematic representation of the energy components

6 Results

6.1 Electricity demand

The consumption for the 8,760 hours of the year has been calculated. The hourly peak load occurs in summer, during the high season. At this hour, the microgrid will have to provide a power of around 2,5 MW. The annual total consumption is equal to around 11 GWh.

The average daily profile is shown in Figure 36:

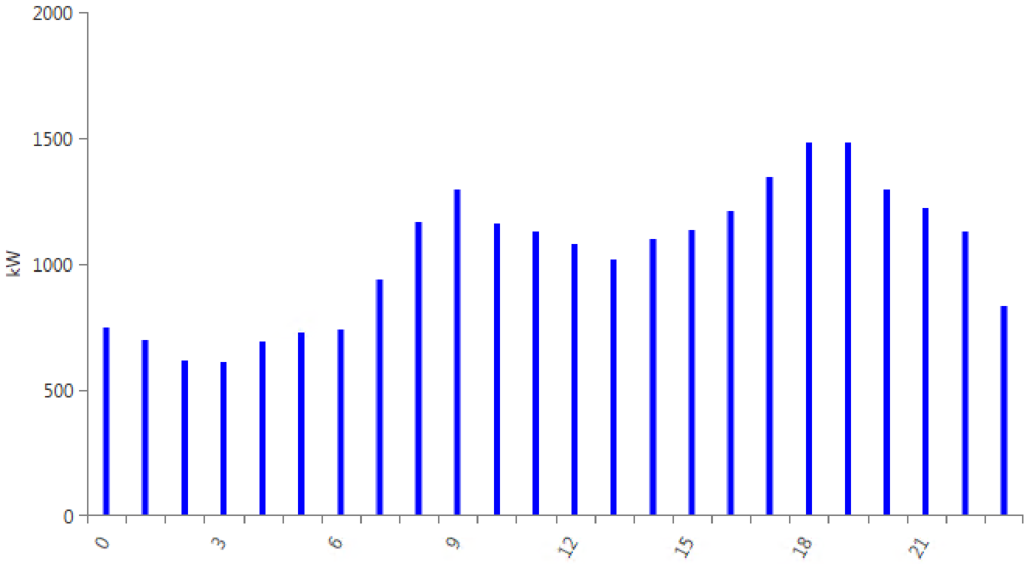


Figure 36: Average daily profile of the electricity demand.

The seasonal variability strongly depends on the monthly occupancy and therefore follows the same trend. A larger difference between the maximum and the minimum load can be observed during the summer compared to winter.

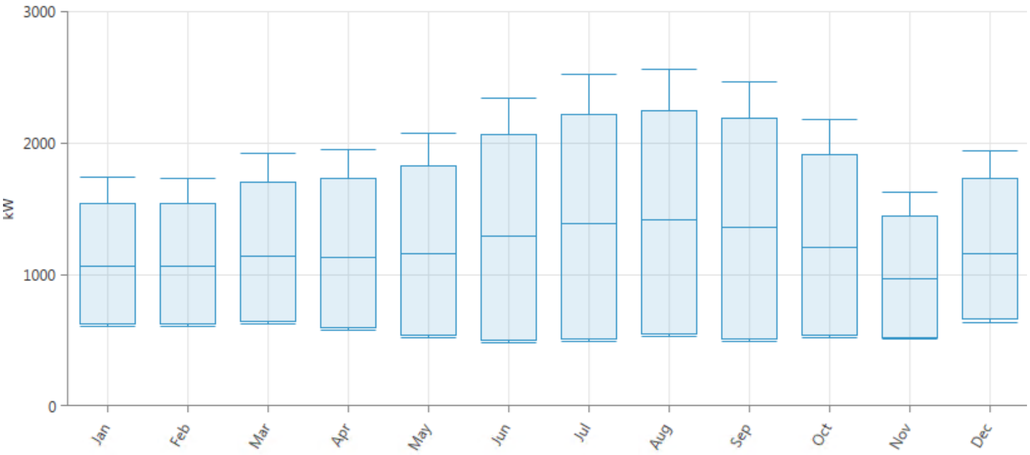


Figure 37: Monthly electricity demand and variability

6.2 Strategy review

The electricity demand of Arkoudi island needs to be supplied by a autonomous system including different technologies. In this study, and according to the local resources potential, it has been decided to evaluate and compare different combinations of energy production components.

The objective is to get a good understanding on the impact of each technology and its potential in the energy system. Therefore, for each addition of a component, an optimization of the system is performed, which means that the optimal installed capacity are determined by minimizing the net present cost of the system.

The "Business as Usual" scenario consists of only diesel generators and no renewable sources of electricity production. Then, the objective is to improve both the economical and environmental performance of the energy system by considering photovoltaic panels. The panels are first considered to be installed as a central plant. On top of that, a battery energy storage system (BESS) is considered as well as wind turbines. Finally, an estimation of the potential for distributed PV (e.g. panels installed on the roofs of buildings) has been carried out. This leads to the following strategies.

Table 6: Breakdown of strategies accounted for the energy system

Strategies	Components
Baseline system : Only generators	⛽
Generators + PV (STRAT1)	⛽ ☀
Generators + PV + BESS (STRAT2)	⛽ ☀ 🔋
Generators + PV + BESS + Wind (STRAT3)	⛽ ☀ 🔋 🌬
Generators + PV distributed + BESS + Wind (STRAT4)	⛽ ☀ 🔋 🌬

For each strategy, an economical and an environmental performances have been assessed. This allowed a final comparison for all energy systems according the different factors such as the net present cost or the renewable fraction.

6.3 Baseline system

The first energy system modeled in HOMER is exclusively made of diesel generators. This serves as baseline strategy when comparing the different system alternatives. The generator design is performed by analyzing the island electricity demand.

Load Analysis

The minimum load demand is equal to 475 kW, while the maximum load is around 2,500 kW. The monotonic load function is shown in Figure 38. It ranks the hourly load demand from the greatest to the smallest load. The purpose of the monotonic load function is to determine how many hours in a year the required power will be greater than a certain power. For example, the Arkoudi's energy system will need to provide 1MW or more during about 6,000 hours. The monotonic function can also be used to design baseload plants and assess how much remaining power will be needed.

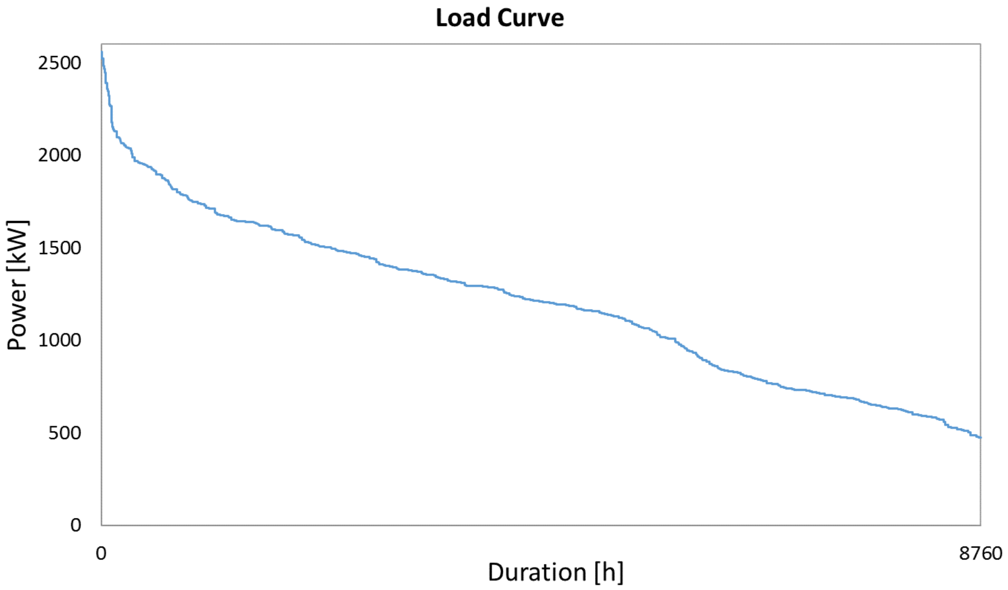


Figure 38: Monotonic load function for Arkoudi electricity demand

Generator Design

As shown in Figure 38, the minimum load power is around 475 kW. Since generators optimally run at 80% of their rated power, the smallest generator capacity is :

$$\text{Minimum Generator Power [kW]} = \frac{\text{Minimum load [kW]}}{0.8} = 593kW \tag{51}$$

The chosen generator is a FG Wilson of 640 kW. Due to the high linearity of the monotonic function and the relatively low minimum load, it has been decided to cover the load only with 640 kW generators.

The total number of generator depends on the maximum load. Again, it is assumed that generators run at 80% of their rated power even at maximum power to ensure a safety margin.

$$\text{Number of generators} = \frac{\text{Maximum load [kW] / 0.8}}{640\text{[kW]}} + 1 \text{ (backup)} = 6 \text{ generators} \tag{52}$$

In order to take into account real life fuel consumption, a additional 15% is added on datasheet values for HOMER simulations. The fuel consumption and the related efficiency curve are shown in Figure 39.

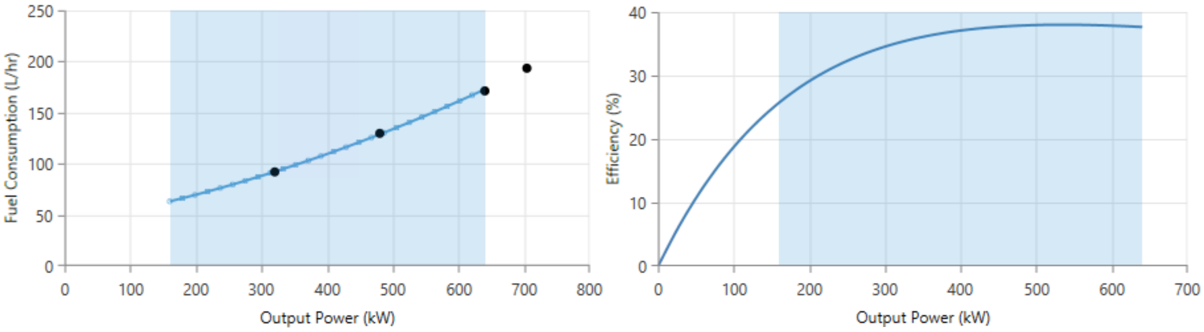


Figure 39: Generator fuel utilization in terms of fuel consumption and efficiency

Table 7: Generator information

	Power [kW]	Initial Capital [$]	Replacement [$]	O&M [$/h]	Lifetime [h]
FG Wilson	640	160,000	120,000	32	40,000
per kW	1	250	187.5	0.05	

Table 8: Fuel information

	Price [$/L]	LHV [MJ/kg]	Density [kg/L]
Diesel	1.35	43.2	0.82

Results

For a 25 years project only with generators to serve the electricity load, the cost breakdown of the energy system is shown in Figure 40. The salvage value is negligible (around $100,000) and is therefore not displayed on the graph.

The fuel expenses account for around 80% of the total system cost, which makes the system extremely dependent on the oil barrel price.

The levelized cost of electricity is calculated as follows :

$$LCOE = \frac{NPC}{\sum_{t=1}^{n} \frac{E_{served,t}}{(1+i)^t}} = \frac{63 \text{ mio } \$}{\sum_{t=1}^{25} \frac{10,511,580[kWh]}{(1+0.059)^t}} = 0.467 \text{ \$/kWh} \qquad (53)$$

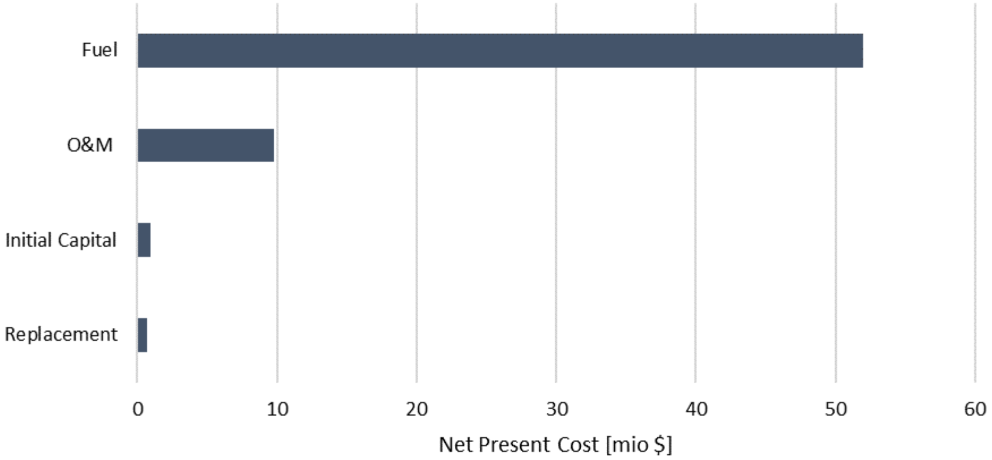


Figure 40: Cost breakdown of the energy system composed of generators.

Table 9: System Results

NPC [mio $]	COE [$/kWh]	Fuel [L/yr]	Ren. fraction [%]	Excess elec. [%]
63.4	0.467	2,980,584	0	0

Discussion
Generators are an old and well-known technology which make them easy to implement for off-grid systems. They need a very small investment capital and ensure a good robustness. Their use needs to be optimized but this can be done by a controller. Nevertheless, generators are extremely polluting and their noise can be disturbing. As shown in Figure 40, they strongly depend on oil price which lowers their supply security. Moreover, with the need of an energy transition and the likely carbon tax to come, the energy cost of oil-based systems could increase even more in the future.

Simulations that integrates renewable energy have shown how these technologies can help to decrease the share of oil dependency as well as reducing the electricity cost.

6.4 STRAT1: Generators + PV

The main objective of this strategy is to compare the impact of installing a central plant with fixed panels compared to a central plant with a horizontal tracking system. Details for simulation inputs are given in subsection 4.3.

The search space for the HOMER optimization goes from 0 to 2500, which is the maximum installed capacities for solar panels without a battery storage system (see subsubsection 4.2.2).

The comparison between a fixed installation and tracking panels are shown in Table 10. The tracking technology is more interesting in terms of cost and renewable fraction when considering the same installed capacity. For both cases, 2.5 MWp of solar panels give the best results in term of total cost minimization.

Table 10: Energy systems information

	NPC [mio $]	COE [$/kWh]	Fuel [L/yr]	Ren. Fraction [%]	Excess electricity [%]
Tracking	51.3	0.378	2,146,534	33.7	13.8
Fixed	53.1	0.39	2,270,547	28.7	10

In order to better understand the influence of different installed capacities, simulations have been performed from 0 to 2500 kWp of tracking panels. Figure 41 shows to NPC and the renewable fraction of the system, in function of the installed capacity. The NPC and the renewable fraction both follow a straight line until around 1,200 kWp where excess electricity starts influencing the financial performance of installing solar panels. Indeed, the excess production will simply be lost since there is no storage technology for this strategy.

Despite the higher percentage of excess electricity when increasing the installed capacity, the optimal system would be the one with 2.5 MWp of solar panels with a tracker. The higher loss related to excess electricity is smaller than the gains achieved by the additional installed capacity. Moreover, it can be seen that excess electricity with the tracking technology is higher. This is due to the much higher electricity production when using a tracker.

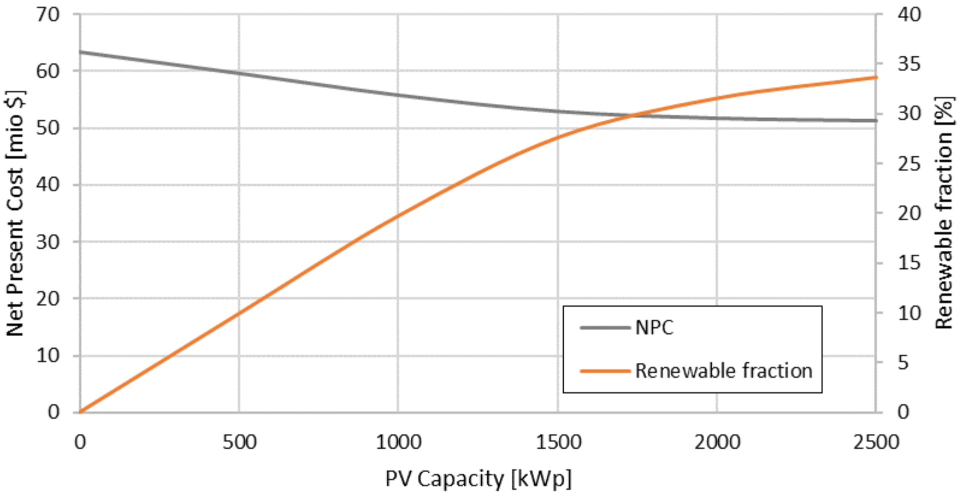


Figure 41: Impact of PV tracking capacity on the NPC and the renewable fraction.

Table 11 shows the differences between the fixed panels and the panels installed with the tracking technology. The capacity factor is higher for tracked panels because they can harvest more energy by following the sun. The real levelized cost of electricity is calculated by considering the electricity served instead of electricity produced. In this way, the excess electricity is considered as lost electricity. The excess value here is the excess electricity divided by the PV production and not the entire energy system production.

The real LCOE represents the cost of serving the electricity, considering that lost electricity has no value. Due to the higher percentage of losses for a tracking system, the real cost of electricity is slightly higher than for fixed panels but they serve much more kWh at this low cost (compared to generators) which makes the system total costs to be lower.

Table 11: Characteristics comparison for fixed panels and the tracking system

	Nominal Power [kWp]	CF [%]	Production [GWh]	Excess [%]	PV LCOE [\$/kWh$_{prod}$]	PV LCOE$_{real}$ [\$/kWh$_{served}$]
Tracking	2,500	23.8	5.2	32.1	0.048	0.070
Fixed	2,500	19.1	4.2	28.0	0.049	0.068

Figure 42 shows the hourly production of the central plant with a tracking system, compared with the hourly electricity demand. An example of three days in September is given here, when the red curve is above the blue curve, the difference is a loss of electricity. HOMER allows the optimization of the trade-off between too much excess electricity in summer and not enough solar production in winter.

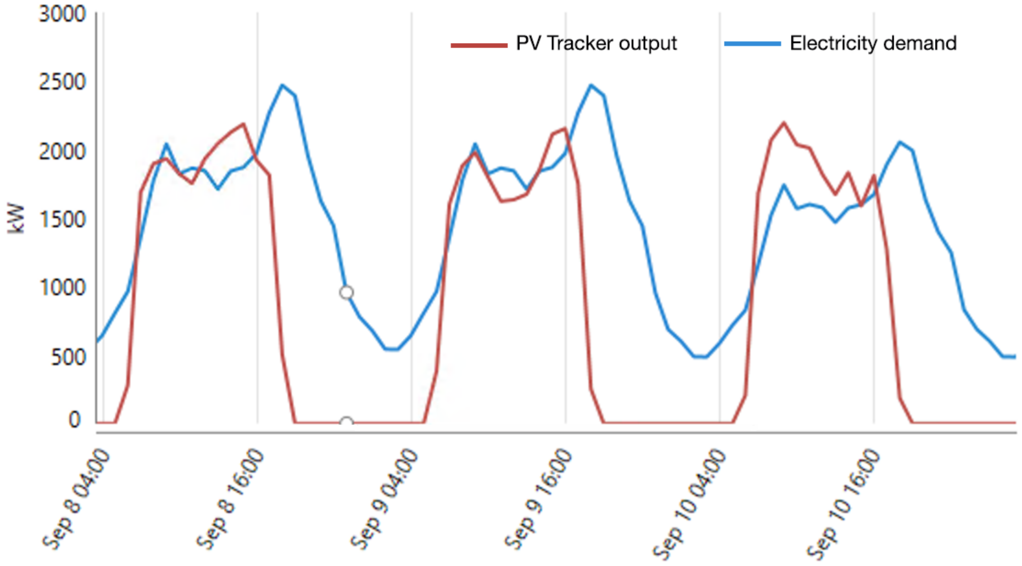


Figure 42: Illustration of hourly production and electricity demand for STRAT1.

Discussion

The integration of solar panels is highly profitable on Arkoudi island due to the good irradiance and therefore a good production in kWh/kWp. The levelized cost of electricity of the energy system could decrease from 0.467 to 0.378 \$/kWh. Tracking system allow to have a better daily distribution with a lower peak at noon and a better production per kWp installed.

The renewable fraction reach up to 33.7% which is already a very high penetration without considering battery storage. In practice, there can be high power fluctuation and a network stabilizer like a battery bank should be implemented. Moreover, it can been seen that there is a potential for using the excess electricity that could be used as "free" energy.

6.5 STRAT2: Generators + PV + BESS

In this strategy, the objective is to integrate a Battery Energy Storage System (BESS) composed of lithium-ion batteries.

Batteries for stability only
Since simulations are based on hourly data, it is difficult to correctly reflect the reality demand-response role of the battery bank. In order to consider that batteries are not used as storage, a minimum state of charge of 90% as been chosen. As shown on table Table 13, the difference in cost over the lifetime of the project is low but network stability would be drastically increased.

Batteries for stability and storage
Now that the network stability is improved thanks to the battery bank, the economic viability of using batteries as storage can be assessed. For this scenario, the PV size can be increased or decreased depending on the synergy with batteries. The constraint of 2.5 MWp does not hold anymore.

For storage purposes, the battery bank is assumed to operate with a maximum DoD of 50% to ensure a lower battery degradation. The optimization has been performed by considering the solar capacity constraint of 8.5 MWp.

Figure 43 shows the LCOE of the energy system for each of the combinations of PV and battery capacities. There is a clear potential of cost reduction by adding these two technologies. Moreover, it can be seen that the minimum occurs with the use of a battery bank which means that the battery storage is economically feasible.

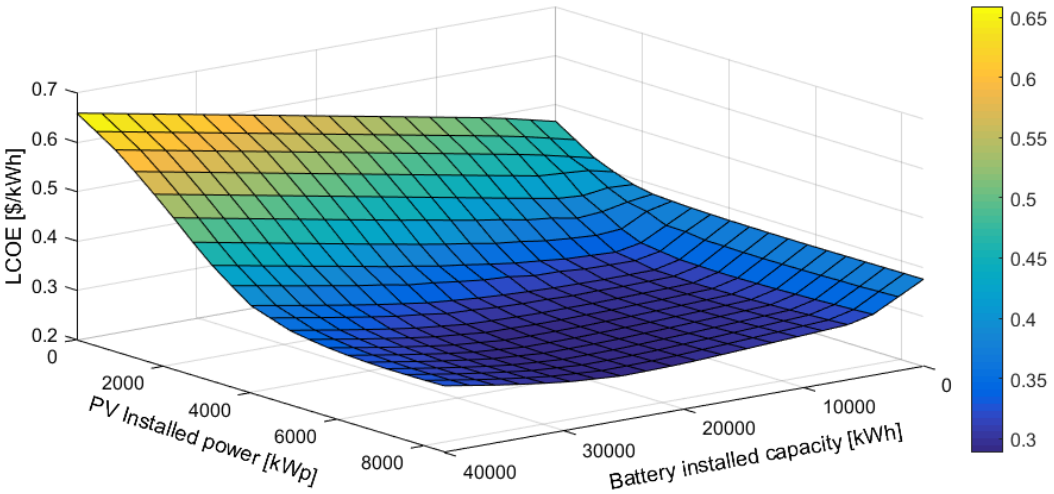


Figure 43: Capacity optimization for PV panels and the battery storage

Table 12: Optimized technology capacities.

	Generators [unit]	PV (tracking) [kWp]	Battery storage [kWh]	Wind Turbines [unit]	DoD [%]
No battery (STRAT1)	6	2,500	0	0	-
Battery as stabilizer	6	2,500	1,000	0	10
Battery as storage	6	7,000	25,000	0	50

Table 13 shows the technical and economical results of the energy system without battery and the new considered systems. The battery storage bank seems to be very interesting by reduction de NPC by around 25%. Besides, the renewable fracton drastically increase from 34% up to 82%, which lowers the use of fuel for generators.

Table 13: Results for the different battery strategies

	NPC [mio $]	COE [$/kWh]	Fuel [L/yr]	Ren. Fraction [%]	Excess electricity [%]
No battery (STRAT1)	51.3	0.378	2,146,534	33.7	13.8
Battery as stabilizer	51.9	0.382	2,124,632	34.3	13.2
Battery as storage	39.1	0.288	574,004	82.0	32.2

Figure 44 shows the hourly production of the central plant with a tracking system and a battery storage bank, compared with the hourly electricity demand. An example of three days in September is given here, when the red curve is above the blue curve, the difference is not a directly loss of electricity anymore, it will be stored in the battery bank until it is fully charged. At this point, and if the panels are still producing more than the load requires, excess electricity will be lost. HOMER allows the optimization of the economical performance by minimizing the net present cost for each installed capacity combinations.

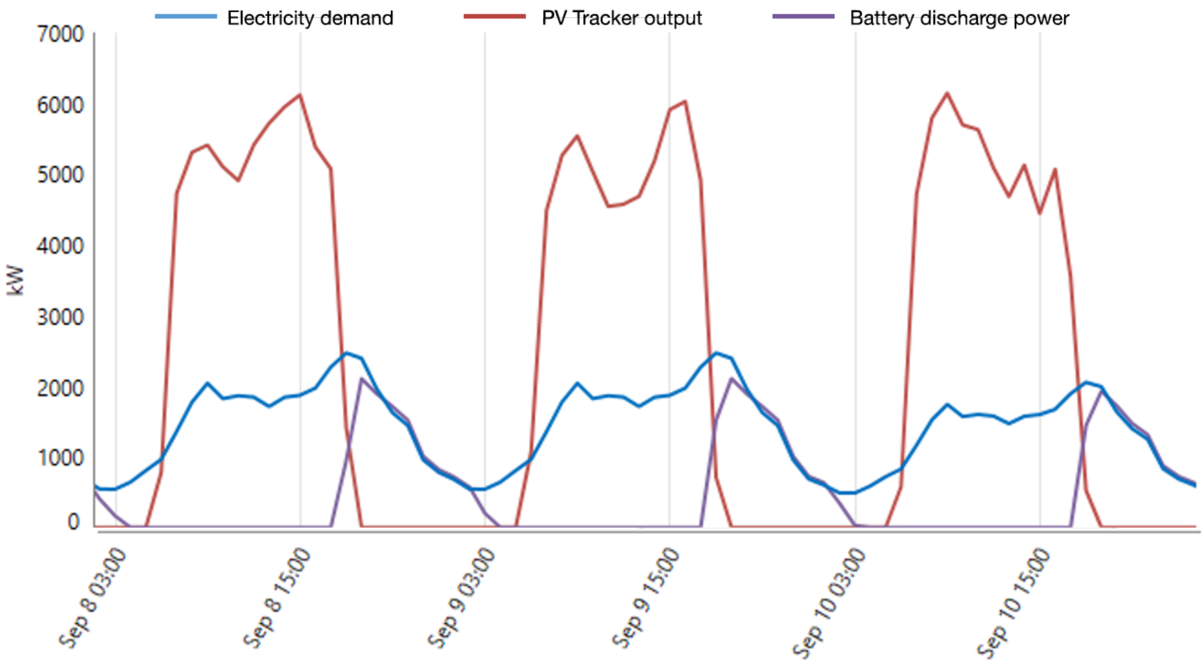


Figure 44: Illustration of hourly production and electricity demand for STRAT2

Discussion

The battery storage seems to be very cost effective compared to diesel generators. It is economically better to install more panels to store electricity and use it when the sun is not shining. The profitability directly depends on the cost of the battery bank. Therefore, a sensitivity analysis will be performed in order to evaluate how the change in price affects the integration of the battery storage. However, it can already been seen that there is a plateau between 15 MWh and 25 MWh after which the levelized cost of electricity increase again.

It can be seen that the excess electricity is very high when using battery as storage, which seems paradoxal. This is due to the potential of installing a lot of solar energy, storing the most electricy possible and loosing the rest. By installed a large capacity, the generator use is decreased and it is more economical to be able to have more solar serving the load even if its production is not fully used.

Still, a PV capacity of 5MWp with a battery bank of 20 MWh could also already provide very good performance (LCOE of 0.293) and decrease the amount of excess electricity to 17% instead of 32.2%. Considering these capacities, the renewable fraction would decrease to 72%.

6.6 STRAT3: Generators + PV + BESS + Wind

The objective of this strategy is to evaluate the benefits of wind turbines integration on the energy system. Instead of increasing the solar panels capacity and producing renewable energy only during daylight, the implementation of this new technology with a total different production pattern can be interesting.

Division in wind turbine parks
The client will need to know the impact of installing a certain number of wind turbines. Furthermore, it is not necessary to optimize the energy system of each single number of installed wind turbines. These two reasons explains the choice of creating three distinctive parks on the island. These parks also allow the client to choose where he would like to install (or not) wind turbines. Wind turbines have been placed on the highest points of the island (see subsubsection 5.2.1). Figure 45 shows the wind parks location and the number of wind turbines per park.

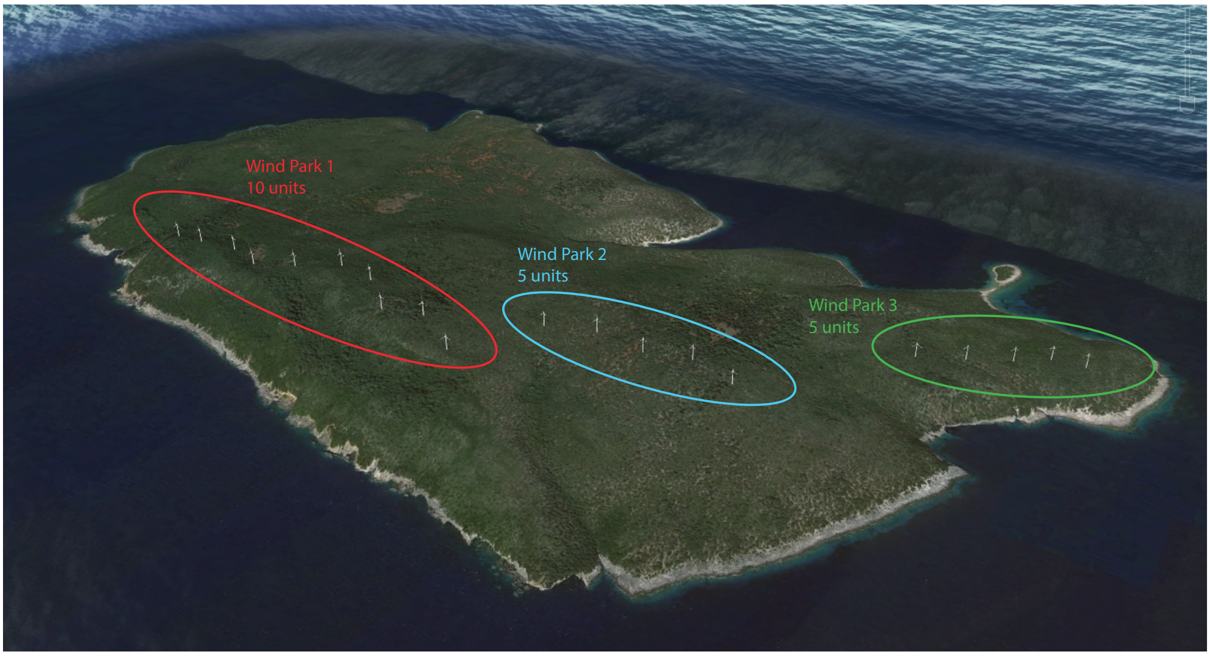


Figure 45: Geographical location of the wind parks.

It is assumed that all wind turbines will produce the same amount of energy. Therefore, the scenario of installing only park 3 is the same than installing only park 2 in terms of energy production. The number of wind turbines for which an optimization needs to be performed are:

- 0 units
- 5 units (only 1 small park)
- 10 units (big park or two small parks)
- 15 units (big park + 1 small park)
- 20 (all parks)

Results
Figure 46 and Figure 47 show the PV power output for a capacity of 5,000 kWp and the wind turbine output of 20 wind turbines (each one having a rated power of 100 kW). It nicely displays

the very different energy output patterns throughout the year of both technologies. The electricity production from PV panels strongly depends on the changing sun irradiation while the turbines output is facing a much more random daily profile. There is an important information that comes up when looking at these two graphs carefully. It can be seen that the wind speed in winter is higher than in summer and can therefore partially compensate the reduction of electricity output from the photovoltaic panels during winter.

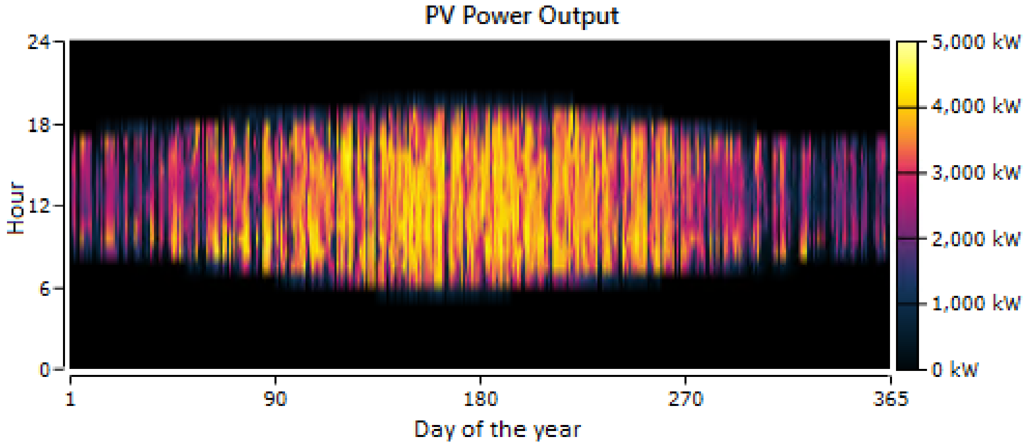


Figure 46: Annual PV power output with the tracking system.

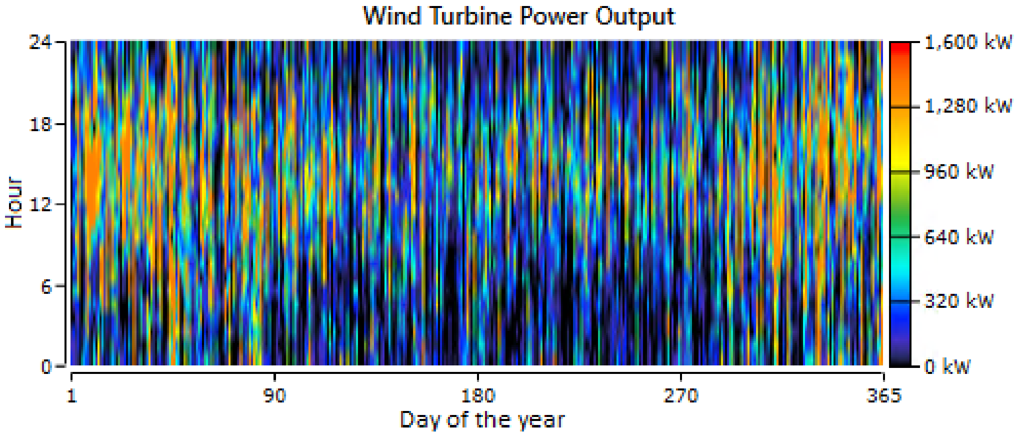


Figure 47: Annual wind turbines power output.

Figure 48 shows the optimization of both the solar plant and the battery storage, considering the installation of 15 wind turbines. This graph can be compared with the one of the precedent strategy where the optimization has been done without any wind turbines.

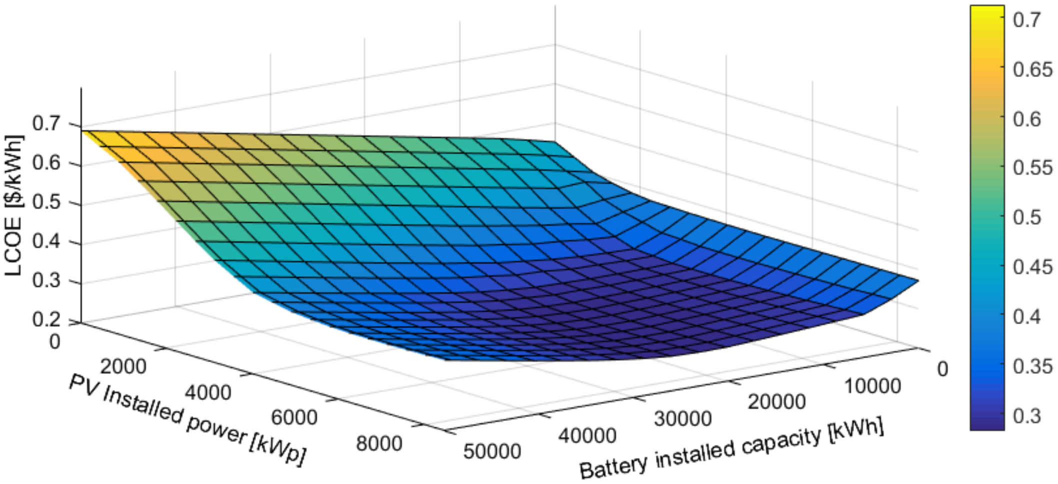


Figure 48: Installed capacity optimization with 15 wind turbines

Table 14 gives the optimal capacities of PV and the battery bank for each scenario of wind parks. Among the 5 scenarios, the optimal one in terms of cost and renewable fraction is the one with 15 wind turbines (Table 15). This combination of energy components is the best achieved during this master thesis in terms of economical profitability.

Table 14: Optimal capacity for each wind park

Generators [unit]	Wind turbines [unit]	PV (tracking) [kWp]	BESS [kWh]
6	0	7,000	25,000
6	5	6,000	20,000
6	10	6,000	20,000
6	**15**	**5,000**	**20,000**
6	20	4,000	15,000

Table 15: Results of the energy system for each wind park

Turbines [units]	NPC [mio $]	COE [$/kWh]	Fuel [L/yr]	Ren. Fraction [%]	Excess electricity [%]
0	39.1	0.288	574,004	82.0	32.2
5	38.3	0.282	634,876	80.3	28.7
10	37.5	0.276	493,619	84.9	30.6
15	**37.1**	**0.273**	**431,030**	**86.9**	**24.3**
20	37.3	0.274	535,912	83.6	20.6

Figure 49 shows the hourly production of the central plant with a tracking system, a battery storage bank and the wind turbines, compared with the hourly electricity demand. An example of three days in September is given here. Compared with the previous strategy, less energy is produced by panels and is replaced by the wind turbines. In September, there is less wind than in winter, which explains the low power output of turbines. The battery bank is used to cover the electricity load in the evening. Generators still need to be used during the night.

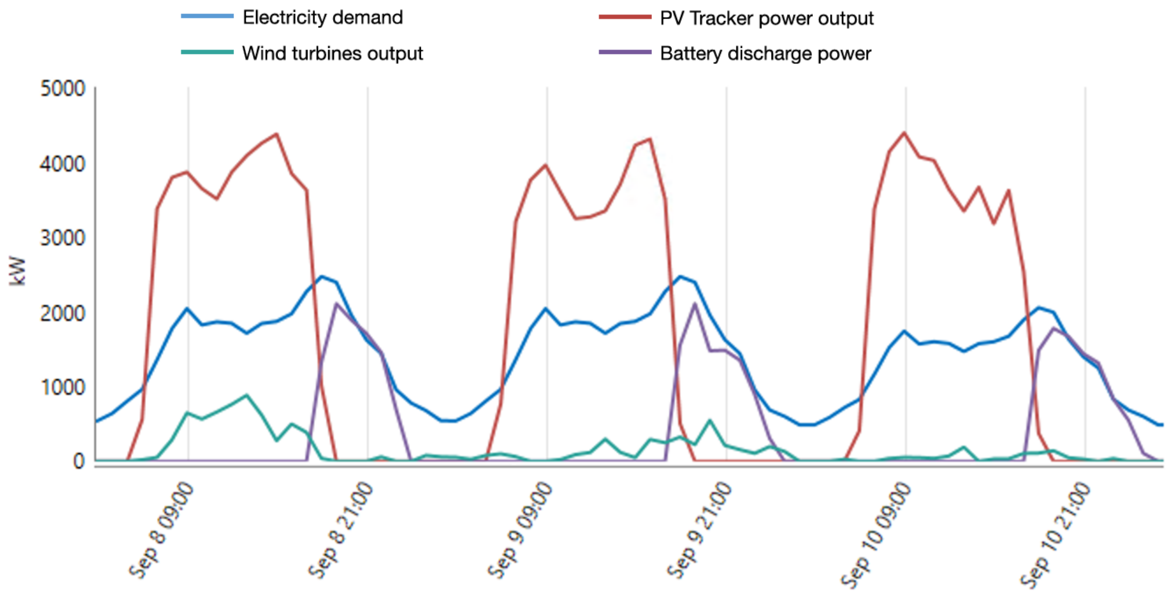


Figure 49: Illustration of hourly production and electricity demand for STRAT3

Discussion

The wind turbines implementation is economically interesting even if it has a small impact on the overall system in terms of cost reduction. The fact that the turbines are small and that the average wind speed is good but not excellent, the LCOE is higher than for large wind farms in optimal locations.

The complementarity between solar and wind production is very important and can be seen in the electrical results. When adding more wind turbines, the renewable production is better distributed through the day and the year which lower the use of solar panels and battery. Indeed, without wind turbines, the system needs to produce a lot of solar energy in order to fill the battery bank for a later use. Moreover, the reduction in these installed capacities allow a strong reduction in excess electricity, which proves that the production is better managed.

6.7 STRAT4: Generators + PV distributed + BESS + Wind

The main difference with the previous strategy is to a consider decentralized solar production instead of one central PV plant. It is assumed that panels are placed on the roofs of buildings that will be built on the island. In order to account for the better use of the distributed electricity, with a lower transmission loss, the efficiency of solar production has been increased by 2%.

Assuming that all 80% of the total roof area is covered by solar panels, the total PV area would be equal to :

$$\text{PV Area} = 0.8 \cdot \text{total roof area} = 0.8 \cdot 60,865\ m^2 = 48,692\ m^2 \tag{54}$$

Assuming panels of 300Wp with a surface of 1.6m^2, the largest capacity that could be installed is equal to around :

$$\text{Max distributed capacity} = \frac{48,692\ m^2 \cdot 0.3\ kWp}{1.6\ m^2} \approx 9.1MWp \tag{55}$$

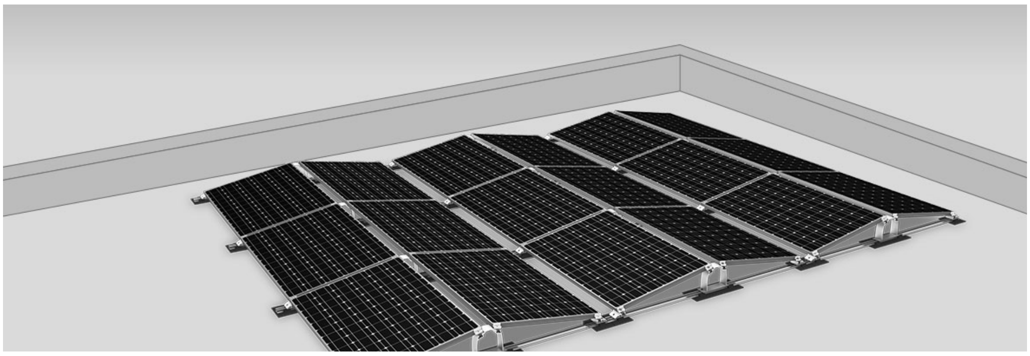


Figure 50: Typical East-West installation on buildings [37]

Compared to a facing south structure, this East-West structure has the following advantages and disadvantage :

Advantages	Disadvantage
- Better production distribution - Lower peak power - Lower cost for panels ballast - Estheticism - More production per m^2	- Less energy output per kWp installed

In order to correctly consider the two orientations east and west, two solar plants have been created in HOMER, one tilted at 10° and facing east, the other one also tilted at 10° but facing west. When considering optimization results, only systems with the same capacity for the two "plants" have been considered assuming that there is a similar quantity of east and west panels.

Results

When considering the installation of solar panels on buildings roofs, the optimal capacity increases to 6 MWp, meaning the 3 MWp is facing east and another 3 MWp is facing west. The higher capacity than for the central plant can be explained by the fact that tracking system has a higher capacity factor and a better daily distribution than East-West plants, even if the latter is better than fields with only one azimuth. Hence, the tracking system can provide more solar energy with slightly less installed power than distributed panels.

Another interesting result is the number of wind turbines. The maximal park should be installed when considering distributed panels. This might be caused by the very little increase in cost for solar installation, which makes the wind turbines to be a little bit more attractive. One should note here that the wind turbine impact is much lower than solar and the difference in system results for 15 or 20 wind turbines is small (see Table 15 in STRAT3)

Table 16: Optimal component capacities for STRAT4.

	Generators [unit]	Wind turbines [unit]	PV (tracking) [kWp]	BESS [kWh]
PV tracking	6	15	5,000	20,000
PV distributed	6	20	6,000	20,000

Table 17: System results for STRAT4.

	NPC [mio $]	COE [$/kWh]	Fuel [L/yr]	Ren. Fraction [%]	Excess electricity [%]
PV tracking	37.1	0.273	431,030	86.9	24.3
PV distributed	39.8	0.293	394,719	88.3	21.4

Figure 51 shows the hourly production of both east and west solar fields and the wind turbines. The discharge power is also shown and all energy components can be compared with the electricity demand in blue. The graph below is the representation of the total solar power output, considering both east and west panels. The production curve is more distributed than a solar plant that would face south.

The battery bank is used to cover the electricity load in the evening, and as for the previous strategy, generators will need to be used during the night to cover the remaining load.

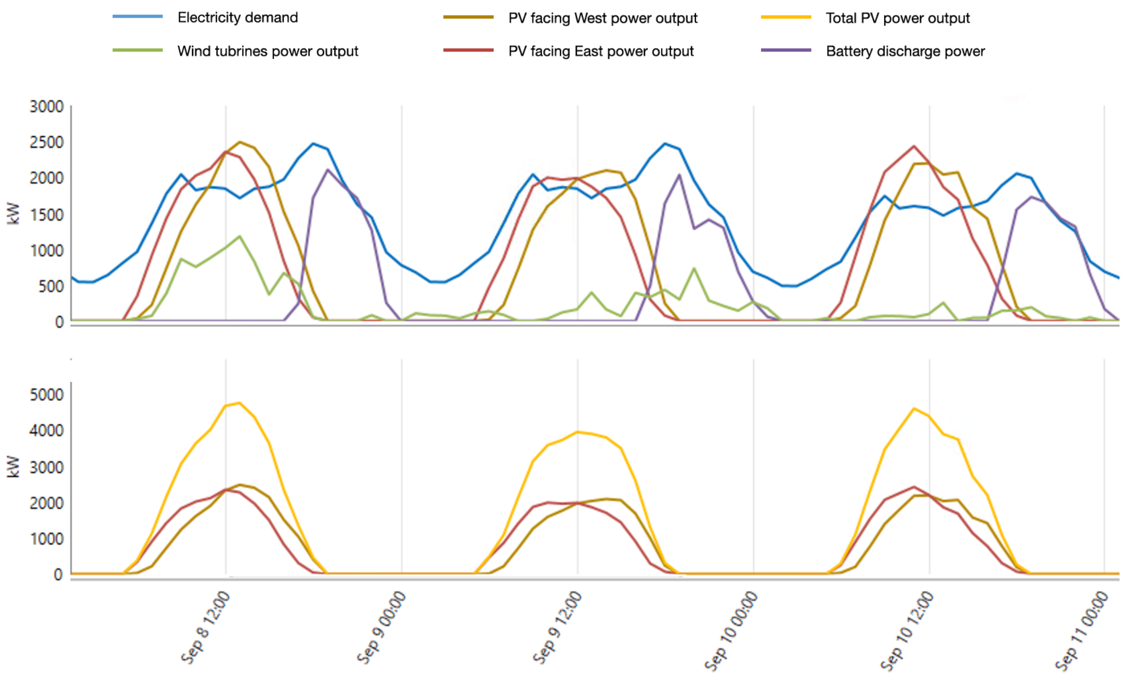


Figure 51: Illustration of hourly production and electricity demand for STRAT4, in summer.

Figure 52 shows the same curves but in winter. In that case, the electricity demand is much lower, with peaks demand reaching 1,500 kW compared with 2,500 kW in summer. There are still days where solar production exceeds the load demand. However, on the 13^{rd} of December in the optimization, the load will always be higher than the solar output, even at noon.

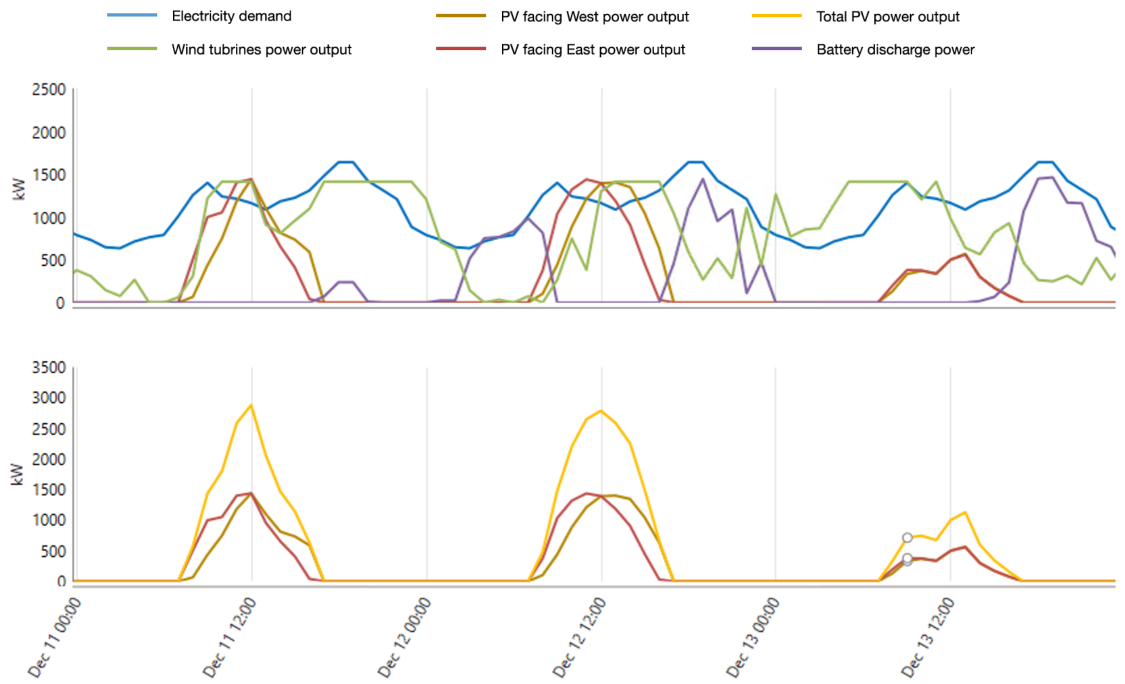


Figure 52: Illustration of hourly production and electricity demand for STRAT4, in winter.

Discussion

The cost of using distributed panels is higher and the levelized cost of electricity increases from 27 to 29 cents per kWh. The increase in investment cost is inevitable because of the need for multiples inverters at production site instead of larger centralized inverters. Moreover, there is a higher installation cost due to the multiple installation sites. On top of that, it is not sure that the network cost of the distributed system would cost less due to less energy flowing in the network. In fact, all transmission lines should be bidirectional and interconnected in order to make sure that overproduction of site i could actually also serve other sites otherwise this electricity would be lost.

Despite these economical and operating principles differences, the consideration of distributed panels instead of a central plant give encouraging results. The net present cost is only 7% higher, while the renewable fraction increases from 86.9 to 88.3%, which makes this strategy least dependent on fuel price.

The most important advantage is that these panels will be integrated to the buildings, without affecting the landscape. With the growing improvement in building integrated panels, there will be very interesting solutions in the near future for colored or semi-transparent panels that can integrate even more aesthetically in the infrastructure. These panels already exist but are currently still too expensive to make them suitable for large applications with economical requirements.

7 Strategies Comparison

There is no initial preferences from the client about which technology he would prefer or which he would not consider. This is why all strategies will be compared on the same criteria, which should give to the owner of the island a good understanding of the main differences between the energy systems. In order to do so, economical and environmental comparison have been performed.

7.1 Economical comparison

In order to estimate the profitability of a standard project, one should calculate the net present value and therefore understand if a certain investment would generate enough revenue. An example would be an investment related to the renovation of a building, creating virtual revenues by reducing the energy cost of heating the building.

In the case of the energy system on Arkoudi Island, there is no proper revenue, since no consumer will pay the electricity on the island. This is why a baseline scenario has to be considered. Each additional investment compared to this scenario could generate a lower price for the electricity production and therefore saving money. As for the example above, this "avoided expenses" is considered as revenues.

The baseline scenario is the energy system including only generators. It represents the simplest way of producing electricity for a remote areas but also a very expensive way. Instead of calculating the net present value of a project compared to the baseline scenario by analyzing the difference in the cashflows, the net present cost of all system is shown in Figure 53. The net present value of considering a certain strategy compared to the baseline scenario is simply the difference in their net present cost.

The main economical characteristics of renewable is clearly visible on this graph : they are based on investment capital and very low operating costs. The more renewable component you install, the higher the capital need for your energy system. It can be seen that the storage brings a important potential for the phase-out of fuel dependency. The percentage of fuel cost in the total cost drops down from 82% in the generators strategy to 16% in the last strategy with distributed panels.

Considering the single criterion of economical performance, the best strategy would be to install a central tracking PV plant, wind turbines and a battery bank as storage. However, it can be seen that the last three strategies are very similar in terms of net present cost. These results are also strongly related to the cost of each technology, whose variation cannot be predicted 100% correctly for the next decade, as well as for fuel price.

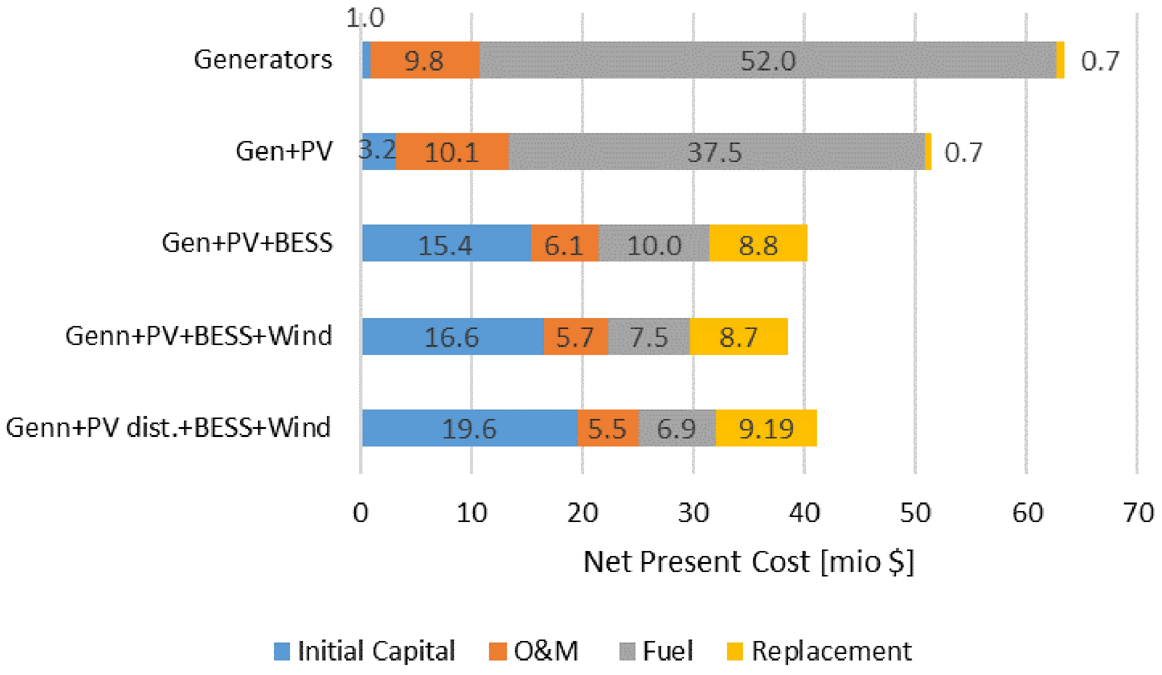


Figure 53: Economical comparison of strategies

7.2 Environmental comparison

The scope of the master thesis is also to evaluate the impact of each system in terms of carbon dioxide emissions.

There are mainly two sources of CO_2 emissions in the energy system. The first one is related to the combustion of fuel in the diesel generators and the second one is the CO_2 emitted during the production of the generators and the renewable components.

CO_2 emissions from fuel combustion are due to the atoms of carbon that oxidize with oxygen to create CO_2. One molecule of CO_2 of 3.67g contains 1g of carbon [3]. During the combustion, it can be assumed that around 99% of the carbon will be emitted as CO_2. The imperfect combustion lead to around 1% of carbon monoxide and unburned hydrocarbons. Sulfur dioxide and nitrogen Oxides will also be emitted but the study will focus on CO_2 emissions. Assuming a generator that consumes 1000 L of diesel (carbon content = 88%, density = 0.85kg/L, the CO_2 emissions will be :

$$\text{CO}_2 \text{ emissions} = 1000[L] \cdot 0.88 \cdot 0.99 \cdot 0.85[kg/L] \cdot 3.67[g_{CO_2}/g_c] = 2,717 \text{ kg} \qquad (56)$$

Assuming a consumption of 0.290L/kWh, 1000L would generate around 3,448 kWh therefore the emissions per kWh of energy is around 780 g per kWh. According to [38], a diesel generator would rather be responsible for around 1,100 gCO_2 per kWh when accounting for the fuel production, transportation and the generator manufacturing.

For the renewables components, the emissions is related to the so-called "embodied energy", the emissions related to the fabrication of renewable components are subjected to a lot of debates, studies and different results. Nevertheless, a study published in *Energy Policy* examined more than 150 studies on the life-cycle CO_2 emissions of a range of wind and solar photovoltaic technologies. The key findings are the following [39]:

- Based on the studies, wind turbines generate an average emission of 34g of CO_2 per kWh over its lifetime, with a lower bound of 0.4g and a higher bound of 364g. Solar mean value is 50g of CO_2 per kWh, with a lower bound of 1 gramm and and higher bound of 218g. The large variability is due to the location, the product origins, the installed capacity and the applied methodology [39].
- The origin of the product manufacturing can be critical, "The same manufacturing process in Germany would result in less than half of the total emissions that such a process would entail in China. This was primarily due to China's significantly greater dependence on black coal for electricity production in comparison with Germany's much greater reliance on natural gas and nuclear power."

The lifetime and the capacity factor also strongly influence the greenhouses gases factor. If the same panels produces twice as in another location, the factor would be halved. In the case of the environmental impact assessment for Arkoudi island the average value for wind and solar is considered.

The battery lithium-ion fabrication is also responsible for CO_2 emissions and needs to be assessed. The study "The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries" [40] has estimated the CO_2 emissions per activity :

- Raw material mining and refining : 60-70 kg CO_2 eq/kWh
- Manufacturing (component + cell + assembly) : 70-110 kg CO_2 eq/kWh
- Recycling : 15 kg CO_2 eq/kWh

The total emissions therefore vary from 145-195 with an average value of 170 kg CO_2 eq/kWh of installed storage.

Table 18: Lifecycle CO_2 emissions

Technology	**gCO_2 eq / kWh**
Generators	1100
Solar panels	50
Wind turbines	30
Battery Storage	136

Figure 54 shows the total CO_2 emissions for the baseline system and the four strategies. The last strategy with distributed panels is the one impacting the least on the environment in terms of CO2 emissions, while the baseline system with only generators would be responsible for a little bit more than twice the emissions of the best strategy.

Although there is a clear improvement when installing renewable energy in the total emissions, the impact of using a battery storage system is very high and should not be forgotten. Indeed, the difference is very small between an energy system only with panels and a system with much more panels coupled with a battery storage. Even if the renewable fraction is increased from 33.7% to 82%, the benefits in terms of CO2 emissions is only about 11%.

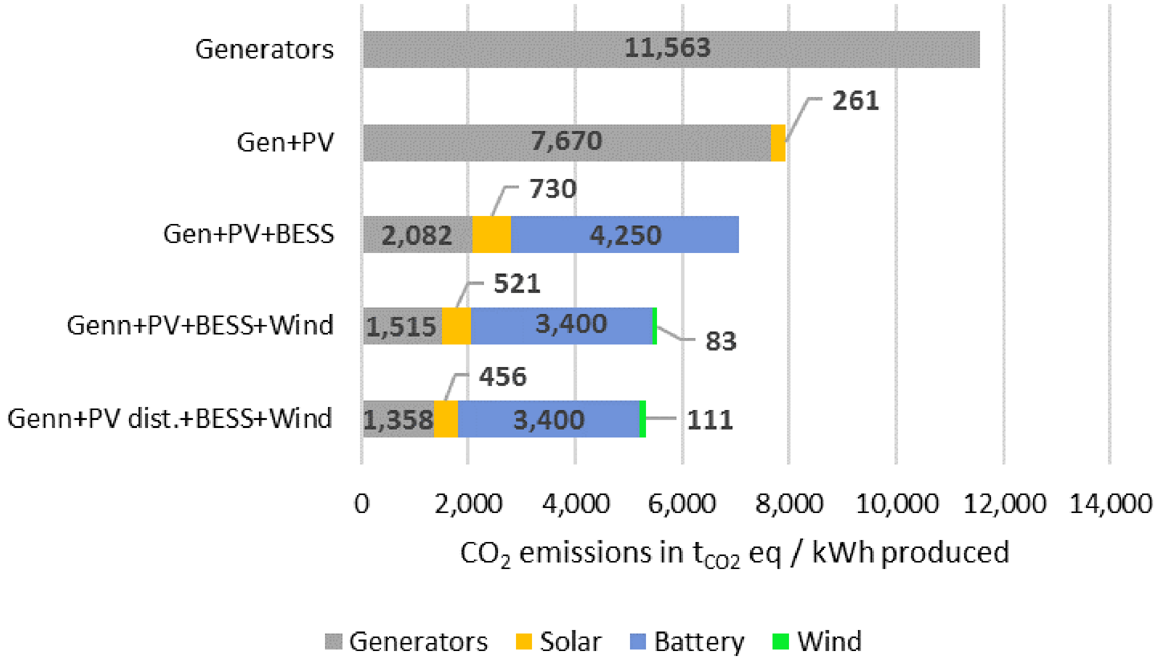


Figure 54: Environmental comparison of the strategies

8 Sensitivity Analysis

Sensitivity analysis is a key step in the project pre-dimensioning. In early stage analysis, some parameters or variables are estimated and they directly influence the technical and economical performance of the project. The uncertainty in these estimations can be the source of wrong decisions. For example, if a wind turbine costs actually 1.5 times than the cost that had been estimated, the related wind park could become to expensive to operate. The decision of commissioning the project is now leading to economical losses even if it has been initially estimated to be profitable. The idea is to determine at which error percentage the project will become unprofitable or should be design in another way. In other words, one can determine the sensitivity of some parameters or variables on the output results. Parameters are fixed values for the optimization such as the discount rate or the fuel price. The components installed capacities are defined as variables because they can vary in the optimization to find the best solution.

In this thesis, multiple parameters and costs have been estimated and not all scenarios can be modeled (for 3 parameters having each one 3 sensitivity values, it represents already 9 scenarios). The sensitivity analysis has been performed in two parts. In the first one, the sensitivity of the battery investment cost and the discount on the optimized components capacities is assessed. When one parameter is changed it is assumed than all other remain the same.
The second part consists of two spider plots who are used to evaluate how a certain output result is affected by different parameters and which of these parameters has the greatest influence. For the Arkoudi energy system, it has been decided to focus on the net present cost and the renewable fraction.

The analysis have been performed on the last strategy (STRAT4) with the distributed photovoltaic panels, the wind turbines and the battery storage. The analysis has been performed on this strategy only and results can be particularly adapted for the last two strategies which have few differences.

8.1 Battery investment cost

One strong uncertainty is the lithium ion battery cost. Their cost are assumed to decrease by 50% to 60% in the coming ten years. Therefore, the real cost that the owner of the island will pay depends on the installation year and the real achieved cost reduction compared to current prices. The battery energy management control has also a cost and should be taken into account but is not part of this master thesis.

Due to the uncertainties for the battery system cost, the optimal components capacities will be optimized for the following investment costs :

- 300 $/kWh (used in Strat. 3 & 4)
- 400 $/kWh
- 500 $/kWh

A replacement cost of 250 $/kWh has been considered if the investment price is 300 $/kWh. Therefore, the replacement costs have been multiplied by the same order of magnitude than for the investment cost, e.g. by 1.33 and 1.66.

Table 19: Optimized technology capacities for the battery cost sensitivity

Battery Cost [$/kWh]	Generators [unit]	PV distributed [kWp]	Battery [kWh]	Wind turbines [unit]
300	6	6,000	20,000	20
400	6	5,000	10,000	20
500	6	5,000	5,000	20

Table 20: System outputs for the battery cost sensitivity

Battery Cost [$/kWh]	NPC [mio $]	COE [$/kWh]	Fuel [L/yr]	Ren. Fraction [%]	Excess electricity [%]
300	39.8	0.293	394719	88.3	21.4
400	42.8	0.315	787852	75.8	21.8
500	43.9	0.323	990373	69.3	26.5

Results in Table 19 and Table 20 shows that even with a battery investment cost of 500$/kWh, the technology is still economically feasible. It optimal capacity drops down to 5 MWh tough. The solar capacity seems to be quite resilient to the change in battery price, as well as wind turbines, for which the maximum value of 20 turbines remains optimal. The net present cost increase from 39.8 to 43.9 millions of dollars. On the other hand, the renewable fraction would decrease to 69.3%.

8.2 Discount rate

According to the experience of Renemig Energy company, a good estimation of the nominal discount rate is 8%. Considering a inflation rate of 2%, the real discount rate can be calculated with Equation 35 and is equal to around 5.9%.

While the discount rate can be well estimated when investing in risk-free rate assets such as treasury bonds, its estimation can be more difficult for a potential project like the one on Arkoudi island. In this case, the viability of the project will be calculated by considering the weighted average cost of capital (WACC) as a discount rate, which is the average cost the company pays for capital from borrowing or selling equity [41].

Due to the uncertainties in the estimation of the WACC, the optimal components capacities will be optimized for the following nominal discount rate :

- 6 %
- 8 % (used for all simulations)
- 10 %

The real discount rate will therefore be respectively equal to 3.9%, 5.9% and 7.8 %, assuming that the inflation rate is 2%.

As for the sensitivity of battery investment cost, the influence of the discount rate will be assessed for the last strategy which considers generators, distributed solar panels, a battery bank and wind turbines.

Table 21: Optimized technology capacities for the discount rate sensitivity

Nom. discount rate [%]	Generators [unit]	PV distributed [kWp]	Battery [kWh]	Wind turbines [unit]
6	6	7,000	20,000	20
8	6	6,000	20,000	20
10	6	5,000	15,000	20

Table 22: System outputs for the discount rate sensitivity

Nom. discount rate [%]	NPC [mio $]	COE [$/kWh]	Fuel [L/yr]	Ren. Fraction [%]	Excess electricity [%]
6	44.3	0.268	344612	89.8	28.3
8	39.8	0.293	394719	88.3	21.4
10	36.2	0.318	611127	81.5	17.4

Results in Table 21 and Table 22 show how the discount rate influence the installed capacity optimization and the technico-economical results. A decrease of the discount rate will tend to encourage the use of technologies with high investment (especially renewables). Indeed, future revenues (or avoided costs) will have a larger impact on the net present value, making these technologies more profitable than with a higher discount rate. The higher the discount rate, the lower the net present cost and the higher the levelized cost of electricity. This is the case for all projects where expenses are higher in the beginning and lower in the future.

8.3 Spider plots

Another way of performing sensitivity analysis is to use spider plots. The objective of these graphs is to evaluate the relative impact of different parameters on one output. Simulations are performed by increasing or decreasing the best estimation of one parameter and the resulting change in the output is shown in the graph.

This method allows to allocate for example more financial resources to the parameter that has the highest impact, in order to better know or estimate its correct value for the project. Similarly, if the impact of a parameter is negligible within a certain range of error, it might be unnecessary to put more work in the estimation of this parameter.

However, it is important to note that the analysis is done separately for each parameter. The combination of two or three estimation deviations can make a project economically unfeasible although it was first estimated to be economically viable.

8.3.1 Influence on the NPC

Figure 55 shows the relative influence of three parameters (the discount rate, the fuel cost and the average wind speed) on the net present cost of the energy system with distributed PV, battery storage and wind turbines.

It can be seen that both the discount rate and the average wind speed have approximately the same influence (same slope) around their best estimate. They have an opposite parabolic curve which means here that if there is a deviation or around 10% or more, the impact on the system is rather more positive for the wind speed than for the discount rate. Indeed, a deviation in wind speed will be more positive or less negative than a same deviation for the discount rate.

The influence of the fuel cost in lower that the other two parameters and this is a good result since one of the objective is to be the most independent from future fuel price variation. The low influence is directly due to the high renewable fraction achieved for STRAT4.

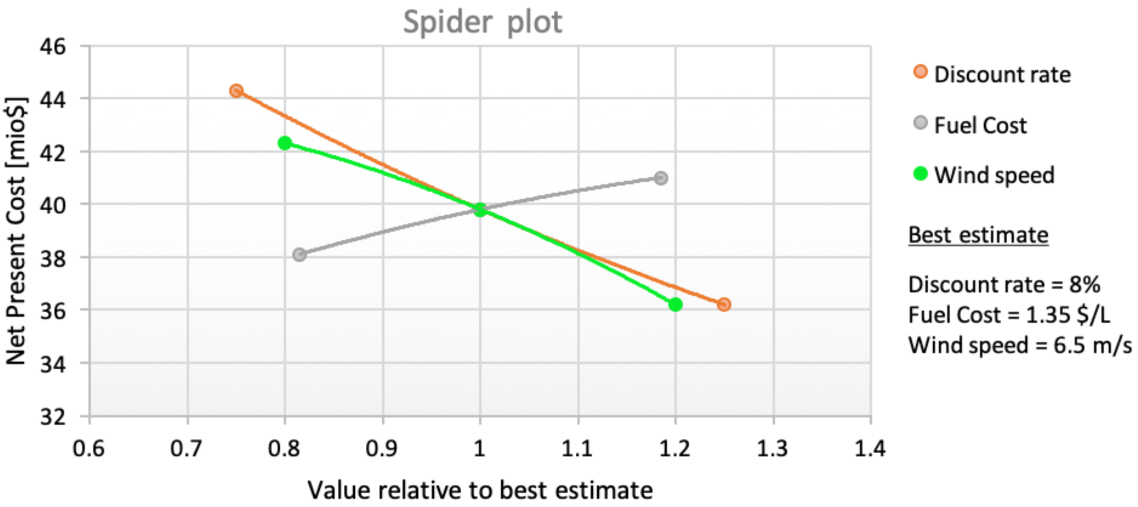


Figure 55: Sensitivity of discount rate, fuel cost and wind speed on the NPC, for STRAT4.

8.3.2 Influence on the renewable fraction

The renewable fraction is an important output to analyze in addition to the net present cost. The optimization of the energy system in performed by minimizing the cost and not by maximizing the renewable fraction. This explains for example why the renewable fraction may fall even if the wind speed is higher. This can be explained by a reduction of another renewable technology due to the high penetration of wind and therefore the remaining electricity needed is rather produced by generators. Another reason can be the limitation in the turbine capacity which does not allow to harvest more power from the wind.

Figure 56 shows that the higher the discount rate, the less attractive become the renewable technologies. This is due to the cash flows sequences of renewables compare with traditional and polluting power generation systems. Indeed, there is always a very large investment cost for solar panels or wind turbines while having very low O&M costs. The investment cost for diesel generators is very low compared with the fuel cost which has to be paid every year. Therefore, when the discount rate is high, investment that occur early in the project's lifetime will have more impact.

The second important information shown by the graph is the higher slope of the fuel cost curve compare with the wind speed. This means that, even if the generators have a low penetration in the energy system, the fuel cost still plays an important role on the renewable fraction of the electricity mix.

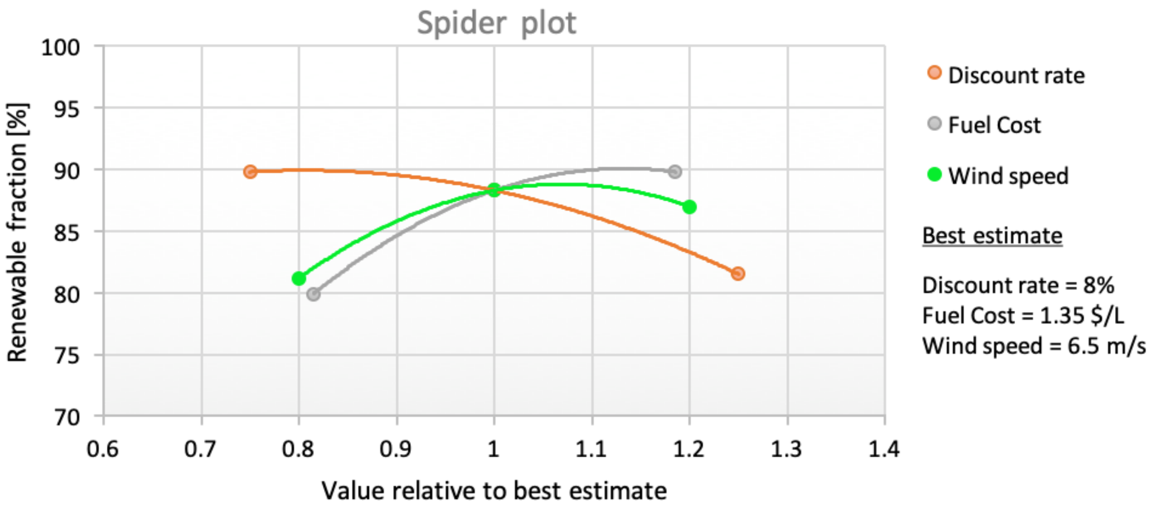


Figure 56: Sensitivity of discount rate, fuel cost and wind speed on the renewable fraction, for STRAT4

9 Conclusion

First of all, results have shown the big potential for renewable technologies integration on Arkoudi island. STRAT4 with distributed panels has shown that 6 MWp of solar panels would be the optimal installed capacity, with a total yearly production of around 9 GWh, whereas the yearly electricity demand on the island has been estimated to 10.5 GWh. On top of that, wind turbines have shown great performances, both economically and with their very low carbon footprint. If the client would be favorable to install larger wind turbines, results have shown that there is a potential for decreasing even more the net present cost and to increase the renewable fraction.

Large installations of renewables inevitably raise the question of the short/long term electricity storage, the network stability and the energy management system. Electricity storage is the current key issue blocking the initiation of an unprecedented energy transition. This problem especially applies for remote areas where no connection with the grid is available. Arkoudi island is a flat island which cannot use pumped hydroelectric storage for long term storage. Simulations have been performed assuming a short term battery storage, but their performance is subjected to debates, especially in terms of grey energy. The environmental assessment showed that the battery bank origins should be chosen very carefully, since the electricity used to produce battery cells is the main cause of lifecycle CO_2 emissions. On top of that, the battery management system costs have not been taken into account in the simulations. One should keep in mind that the batteries need to be managed very carefully to ensure a good electricity quality and an optimized lifetime. This cost can affect the economical optimality and should be analyzed more in details.

In this thesis, the predimensioning of components in mainly based on the power and energy output rather than the network stability. Therefore, an deeper study on the electrical feasibility should be done to ensure a proper operation of the energy system. In fact, network characteristics and the practical operating principles were not the scope of the project. However, it is clear that increasing the number of electricity production components increases the energy system complexity, too. The network cost have been assumed to be equal for each strategy, which might not be the case in reality. Indeed, the peak power of solar installations at noon need to be harvest correctly and safely by the network. High fluctuations in energy production, due to the intermittency of renewables, also needs to be controlled and this adds a cost. More detailed simulations with a minute or second scale instead of an hourly demand needs to be carried out to evaluate how the perturbation in the electricity network could be balanced, especially by a battery bank.

Another way of controlling the production intermittency or the energy shifting, is to define deferrable loads. These loads requires a certain quantity of energy but the timing is not important. They could be used when too much electricity is produced, avoiding excess electricity to be lost. In the same way, they can be temporarily shifted to decrease the power demand during critical periods.

An interesting future work on this case study could be the integration of the hydrogen storage and the use of fuel cells. Hydrogen-based vehicles could also be used in order to reduce the night demand due to electrical chargers. Moreover, a energy system 100% based on renewables could be developed. However, a important part of the work should be given to the electricity network design and its technical limits for renewables integration.

A Appliances

		Appliances hourly profiles																							
	Electrical Power W/m^2	1 [-]	2 [-]	3 [-]	4 [-]	5 [-]	6 [-]	7 [-]	8 [-]	9 [-]	10 [-]	11 [-]	12 [-]	13 [-]	14 [-]	15 [-]	16 [-]	17 [-]	18 [-]	19 [-]	20 [-]	21 [-]	22 [-]	23 [-]	24 [-]
Double bedroom	10	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.8	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.0	0.6	0.4	0.2	0.2
Suite	7.0	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.8	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.0	0.6	0.4	0.2	0.2
Grande suite	6	0.2	0.1	0.1	0.1	0.1	0.1	0.2	0.4	0.8	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.4	1.0	0.6	0.4	0.2	0.2
Restaurant	3	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.4	0.4	0.6	1.0	1.0	0.1	0.1	0.1	0.1	0.4	0.4	0.6	1.0	0.8	0.6
Restaurant kitchen	150	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.4	0.6	0.8	1.0	1.0	0.6	0.4	0.1	0.1	0.4	0.8	1.0	1.0	0.4	0.2	0.1
Business Center	12.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	0.4	0.6	1.0	0.8	0.6	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Event Halls	3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.6	0.6	0.6	0.6	0.6	1.0	1.0	1.0	0.6	0.2
SPA	80.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.6	0.6	0.3	0.1	0.1	0.1	0.8	1.0	1.0	0.7	0.3	0.3	0.3	0.3	0.1
Reception	9	0.2	0.1	0.1	0.1	0.1	0.1	0.5	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	0.5	0.5	0.5	0.3
Swimming pools	80	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Car charging station (at habitation)	11000 [W]	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.2	0.1	0.3	0.3	0.2
Car charging station	11000 [W]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.3	0.3	0.2	0.2	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Boat charging station	50000 [W]	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.5	0.5	0.3	0.0	0.0	0.0
House	14	0.2	0.2	0.1	0.1	0.1	0.3	0.4	0.5	0.7	0.5	0.3	0.3	0.5	0.4	0.2	0.2	0.3	0.4	0.6	0.6	0.5	0.2	0.2	0.2
Villa	14	0.2	0.2	0.1	0.1	0.1	0.3	0.4	0.5	0.7	0.5	0.3	0.3	0.5	0.4	0.2	0.2	0.3	0.4	0.6	0.6	0.5	0.2	0.2	0.2
Tennis court inside	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.8	1.0	1.0	0.8	0.8	0.8	1.0	1.0	0.8	0.5	0.8	0.8	0.8	0.5	0.5	0.1
Tennis court outside	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.8	1.0	1.0	0.8	0.8	0.8	1.0	1.0	0.8	0.5	0.8	0.8	0.8	0.5	0.5	0.1
Fitness	3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.8	1.0	1.0	0.8	0.8	0.8	1.0	1.0	0.8	0.5	0.8	0.8	0.8	0.5	0.5	0.1
Basket court inside	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.8	1.0	1.0	0.8	0.8	0.8	1.0	1.0	0.8	0.5	0.8	0.8	0.8	0.5	0.5	0.1
Basket court outside	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.8	1.0	1.0	0.8	0.8	0.8	1.0	1.0	0.8	0.5	0.8	0.8	0.8	0.5	0.5	0.1
Football court outside	0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.8	1.0	1.0	0.8	0.8	0.8	1.0	1.0	0.8	0.5	0.8	0.8	0.8	0.5	0.5	0.1
Physiotherapy center	3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	0.4	0.6	1.0	0.8	0.6	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Warehouse	1	0.2	0.2	0.2	0.2	0.2	0.5	0.8	1.0	1.0	0.8	1.0	0.5	0.8	1.0	1.0	0.8	0.8	0.8	0.5	0.5	0.5	0.5	0.2	0.2
Lounge	4	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.6	1.0	0.4	0.4	0.5	0.7	1.0	0.6	0.4	0.4	0.4	0.1	0.1	0.1	0.1
Open Cinema	20	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	1.0	1.0	1.0	0.6	0.2
Museum	3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	1.0	1.0	0.8	0.4	0.4	1.0	1.0	1.0	1.0	0.6	0.6	0.1	0.1	0.1	0.1
Church	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	1.0	1.0	0.5	0.2	0.3	0.4	0.6	0.6	0.6	0.6	1.0	1.0	0.6	0.2	0.1
Mosque	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	1.0	1.0	0.5	0.2	0.3	0.4	0.6	0.6	0.6	0.6	1.0	1.0	0.6	0.2	0.1
Synaguogue	1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	1.0	1.0	0.5	0.2	0.3	0.4	0.6	0.6	0.6	0.6	1.0	1.0	0.6	0.2	0.1
Shops (no alimentation)	3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.1	0.1	0.1	0.1
Shops (with alimentation)	125	0.2	0.2	0.2	0.2	0.2	0.2	0.2	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.2	0.2	0.2	0.2
Hospital room	10	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.8	0.6	0.4	0.2	0.2
Treatment room	20	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	0.4	0.6	1.0	0.8	0.6	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Operation room	30	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	0.4	0.6	1.0	0.8	0.6	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Nautical cabin	8	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	0.6	0.6	1.0	0.8	0.6	0.4	0.3	0.3	0.2	0.1	0.1	0.1
Bar	15	0.8	0.6	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	0.5	0.9	1.0	0.9
Data room	4000	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
IT room	4000	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Meeting room	7	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.6	1.0	0.4	0.1	0.1	0.6	1.0	0.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Office	11	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	0.4	0.6	1.0	0.8	0.6	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Waster water treatment	400	0.2	0.2	0.2	0.2	0.2	0.2	0.3	0.4	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.6	0.4
Environmental Lighting	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Mega Yacht Pier	100000 [W]	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Private Retreat	10	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	0.4	0.6	1.0	0.8	0.6	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Villa Nursery	8	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.8	1.0	0.8	0.4	0.6	1.0	0.8	0.6	0.5	0.5	0.5	0.1	0.1	0.1	0.1
Slaughter House	250	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Big fridges	30000 [W]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.7	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Ice Making	20000 [W]	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.7	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.7	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Irrigation	100000 [W]	0.0	0.0	0.0	0.0	1.0	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	0.0
Water Pumping	500000 [W]	0.1	0.1	0.1	0.1	0.1	0.2	0.5	0.7	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.7	0.8	1.0	1.0	0.8	0.7	0.6	0.5	0.2

B Lighting

						Lighting hourly profiles																							
	Illuminance	luminous efficacy	Design factor	Utilance	Lighting power	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	lux	lm/W	-	-	W/m^2	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]	[-]
Double bedroom	150	134	1.25	0.7	2.0						0.1	0.6	0.4	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.2	0.3	0.4	0.8	0.7	0.4
Suite	150	134	1.25	0.7	2.0						0.1	0.6	0.4	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.2	0.3	0.4	0.8	0.7	0.4
Grande suite	150	134	1.25	0.7	2.0						0.1	0.6	0.4	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.6	0.2	0.3	0.4	0.8	0.7	0.4
Restaurant	300	134	1.25	0.9	3.1											1.0	1.0	1.0	1.0	1.0				1.0	1.0	1.0	1.0	1.0	
Restaurant kitchen	500	134	1.25	0.7	6.7						1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0				1.0	1.0	1.0	1.0	1.0			
Business Center	300	134	1.25	0.9	3.1								1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Event Halls	200	134	1.25	0.9	2.1														1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
SPA	50	134	1.25	0.9	0.5									0.3	0.5	0.5	0.3	0.5	0.6	0.6	0.8	0.8	0.8	0.7	0.3	0.3	0.3	0.3	0.1
Reception	300	134	1.25	0.8	3.5	0.5	0.5	0.5	0.5	0.5	0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Swimming pools	300	134	1.25	0.7	4.0								1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0					
Car charging station (at habitation)																													
Car charging station																													
Boat charging station																													
House	70	134	1.25	0.7	0.9							0.3	0.8	0.6										0.2	0.3	0.4	0.8	0.7	0.4
Villa	70	134	1.25	0.7	0.9							0.3	0.8	0.6										0.2	0.3	0.4	0.8	0.7	0.4
Tennis court inside	500	134	1.25	1.0	4.7								1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Tennis court outside	300	134	1.25	1.0	2.8																			1.0	1.0	1.0	1.0	1.0	
Fitness	300	134	1.25	0.8	3.5									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0							
Basket court inside	500	134	1.25	1.0	4.7									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Basket court outside	300	134	1.25	1.0	2.8																			1.0	1.0	1.0	1.0	1.0	
Football court outside	300	134	1.25	1.0	2.8																			1.0	1.0	1.0	1.0	1.0	
Physiotherapy center	300	134	1.25	0.9	3.1									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0							
Warehouse	100	134	1.25	0.7	1.3						1.0	1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Lounge	200	134	1.25	0.8	2.3							1.0		1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0				
Open Cinema																													
Museum	300	134	1.25	0.8	3.5									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0					
Church	50	134	1.25	0.7	0.7									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Mosque	50	134	1.25	0.7	0.7									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Synaguogue	50	134	1.25	0.7	0.7									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Shops (no alimentation)	300	134	1.25	0.9	3.1									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Shops (with alimentation)	300	134	1.25	0.9	3.1									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Hospital room	100	134	1.25	0.8	1.2								1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Treatment room	500	134	1.25	0.8	5.8									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Operation room	500	134	1.25	0.8	5.8									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Nautical cabin	100	134	1.25	0.8	1.2									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Bar	100	134	1.25	0.7	1.3	0.8	0.8	0.4																		0.7	1.0	1.0	1.0
Data room	100	134	1.25	0.9	1.0									0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5						
IT room	100	134	1.25	0.9	1.0									0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5						
Meeting room	500	134	1.25	0.9	5.2									1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Office	300	134	1.25	0.7	4.0								0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5					
Waster water treatment	300	134	1.25	0.8	3.5							1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	
Environmental Lighting	10	134	1.25	1.0	0.1	0.5	0.5	0.5	0.5	0.5															0.5	1.0	1.0	1.0	1.0
Mega Yacht Pier																													
Private Retreat																													
Villa Nursery	150	134	1.25	0.7	2.0																		0.5	1.0	1.0	1.0	1.0	1.0	
Slaughter House	200	134	1.25	0.8	2.3								0.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
Big fridges	500	134	1.25	1.8	2.6								1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0						
Ice Making																													
Irrigation																													
Water Pumping																													

C Heating & Cooling

Table 23: Cooling degree hours

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	0	0	0	0	0	0	0.5	1.5	0	0	0	0
2	0	0	0	0	0	0	0	1	0	0	0	0
3	0	0	0	0	0	0	0	1	0	0	0	0
4	0	0	0	0	0	0	0.5	1.5	0	0	0	0
5	0	0	0	0	0	0	1.5	2.5	0	0	0	0
6	0	0	0	0	0	0.5	2.5	3.5	1	0	0	0
7	0	0	0	0	0	1	3	4	1.5	0	0	0
8	0	0	0	0	0	2	4	5	2.5	0	0	0
9	0	0	0	0	0	3	5	6	3.5	0	0	0
10	0	0	0	0	0	3.5	5.5	6.5	4	0	0	0
11	0	0	0	0	0.5	4.5	6.5	7.5	5	1	0	0
12	0	0	0	0	1.5	5.5	7.5	8.5	6	2	0	0
13	0	0	0	0	2	6	8	9	6.5	2.5	0	0
14	0	0	0	0	2	6	8	9	6.5	2.5	0	0
15	0	0	0	0	1.5	5.5	7.5	8.5	6	2	0	0
16	0	0	0	0	1	5	7	8	5.5	1.5	0	0
17	0	0	0	0	0	4	6	7	4.5	0.5	0	0
18	0	0	0	0	0	3	5	6	3.5	0	0	0
19	0	0	0	0	0	2	4	5	2.5	0	0	0
20	0	0	0	0	0	1	3	4	1.5	0	0	0
21	0	0	0	0	0	0	2	3	0.5	0	0	0
22	0	0	0	0	0	0	1.5	2.5	0	0	0	0
23	0	0	0	0	0	0	1.5	2.5	0	0	0	0
24	0	0	0	0	0	0	1	2	0	0	0	0

Table 24: Heating degree hours

Hour	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	11.5	11	9.5	6.5	2.5	0	0	0	0	2	6	10.5
2	12	11.5	10	7	3	0	0	0	0	2.5	6.5	11
3	12	11.5	10	7	3	0	0	0	0	2.5	6.5	11
4	11.5	11	9.5	6.5	2.5	0	0	0	0	2	6	10.5
5	10.5	10	8.5	5.5	1.5	0	0	0	0	1	5	9.5
6	9.5	9	7.5	4.5	0.5	0	0	0	0	0	4	8.5
7	9	8.5	7	4	0	0	0	0	0	0	3.5	8
8	8	7.5	6	3	0	0	0	0	0	0	2.5	7
9	7	6.5	5	2	0	0	0	0	0	0	1.5	6
10	6.5	6	4.5	1.5	0	0	0	0	0	0	1	5.5
11	5.5	5	3.5	0.5	0	0	0	0	0	0	0	4.5
12	4.5	4	2.5	0	0	0	0	0	0	0	0	3.5
13	4	3.5	2	0	0	0	0	0	0	0	0	3
14	4	3.5	2	0	0	0	0	0	0	0	0	3
15	4.5	4	2.5	0	0	0	0	0	0	0	0	3.5
16	5	4.5	3	0	0	0	0	0	0	0	0	4
17	6	5.5	4	1	0	0	0	0	0	0	0.5	5
18	7	6.5	5	2	0	0	0	0	0	0	1.5	6
19	8	7.5	6	3	0	0	0	0	0	0	2.5	7
20	9	8.5	7	4	0	0	0	0	0	0	3.5	8
21	10	9.5	8	5	1	0	0	0	0	0.5	4.5	9
22	10.5	10	8.5	5.5	1.5	0	0	0	0	1	5	9.5
23	10.5	10	8.5	5.5	1.5	0	0	0	0	1	5	9.5
24	11	10.5	9	6	2	0	0	0	0	1.5	5.5	10

D Buildings Information

Location	Energy reference Area [m^2]	Footprint Area[m^2]	Sleeping Guests	Car chargers
Main Marina	550	750	0	
Cultural Village	900	900	0	
Religious village	600	600	0	
Sport village	2,885	2,885	0	5
Agriculture Village	1,000	2,000	0	
Private Villa 1 - 20	16,000	8,000	120	20
Houses village 1 - 5	10,000	5,000	200	25
Private Retreat 1 - 10	500	500	0	
Main Hotel	84,940	28,313	140	20
Commercial Center	3,000	3,000	0	5
Nursery and kindergarten	1,000	1,000	0	
Main hospital	2,360	1,180	0	5
Small Marinas 1-4	800	800	0	
Beaches 1-5	1,750	1,750	0	
Detox clinic	1,070	357	0	
Employees Houses	4,515	1,505	0	10
Heliport	150	350	0	
Telecommunication center	25	25	0	
IT Center	25	25	0	
Offices	560	560	0	5
Guest offices	800	800	0	
Waste treatment center	400	350	0	
Firehouse	180	165	0	
Police station	100	50	0	

E Load type and information

Location	**Load Group**	**Nb**	**Area [m^2]**	
Main Marina				
	Restaurant		200	
	Restaurant kitchen		200	
	Warehouse		200	
	Lounge		150	
	Mega Yacht pier		1	unit
	Boat Charging Station		5	units
	Environment Lighting		3,000	
Cultural Village				
	Open ancient theater			
	Open Cinema			
	Museum		500	
	Restaurant			
	Restaurant		200	
	Restaurant kitchen		200	
	Environment Lighting		3,600	
Religious village				
	Church		200	
	Mosque		200	
	Synagogue		200	
	Environment Lighting		2,400	
Sport village				
	Tennis courts , 2 inside		1,600	
	Tennis courts , 2 outside		1,600	
	Basket courts, 1 inside		420	
	Basket courts, 1 outside		420	
	Football court outside		600	
	2 beachvolley courts		324	
	Swimming pool 25m open/close		375	
	Fitness club		400	
	Spa		700	
	Physiotherapy Center		300	
	Business center		100	
	Car Charging Station		5	units
	Environment Lighting		11,540	
Agriculture Village				
	Slaughter house		200	
	Dairy products production		1	unit
	Vegetables packing		1	unit
	Meat fridges		1	unit
	Vegetables fridges		1	unit
	Fish fridges		1	unit
	Ice Making		1	unit
	Irrigation		1	unit

Location	**Load Group**	**Nb**	**Area [m^2]**	
	Warehouse		1,000	
	Agriculture Machinery		6	units
	Environment Lighting		8,000	
Private Villa 1 - 20				
	Villa	20	16,000	
	Car Charging Stations		20	units
	Environment Lighting		3,200	
Houses village 1 - 5				
	Village 1		2,000	
	Village 2		2,000	
	Village 3		2,000	
	Village 4		2,000	
	Village 5		2,000	
	Car Charging Station		25	units
	Environment Lighting		20,000	
Private Retreat 1 - 10				
	1 bedroom	10	500	
	Environment Lighting		10,000	
Main Hotel				
	Double bedroom	40	1,200	
	Suite	20	1,200	
	Grande Suite	10	800	
	Restaurant		280	
	Restaurant kitchen		280	
	Business Center	14	70	
	Offices (employees)	14	70	
	Event halls		1,500	
	Spa		500	
	Fitness		200	
	Reception		500	
	Swimming pools	5	1,000	
	Car Charging Station		20	units
	Environment Lighting		113,253	
Commercial Center				
	Shops	15	1,500	
	Food shop	5	500	
	Restaurants	2	500	
	Restaurants kitchen	2	500	
	Car Charging Station		5	units
	Environment Lighting		12,000	
Nursery and kindergarten				
	Villa for nursery		1,000	
	Environment Lighting		4,000	
Main hospital				

Location	**Load Group**	**Nb**	**Area [m^2]**	
	Hospital Rooms	20	1,000	
	Treatment Rooms	10	250	
	Operation Rooms	3	60	
	Intensive Care Units	5	150	
	Restaurant		200	
	Restaurant kitchen		200	
	Offices		100	
	Physiotherapy Center		400	
	Car Charging Station		5	units
	Environment Lighting		4,720	
Small Marinas 1-4				
	Bar		200	
	Nautical cabin		800	
	Environment Lighting		3,200	
	Boat Charging Station		10	units
Beaches 1-5				
	Bar		500	
	Lifeguard cabin		1,250	
	Environment Lighting		7,000	
Detox clinic				
	Hospital Rooms	10	500	
	Treatment Rooms	5	100	
	Intensive Care Units		20	
	Restaurant hall		200	
	Restaurant hall		200	
	Offices		50	
	Environment Lighting		1,427	
Employees Houses			4,515	
	Double bedroom	194	2,905	
	Restaurant hall		920	
	Kitchen		46	
	Offices	92	460	
	Fitness		184	
	Car Charging Station		20	units
	Environment Lighting		6,020	
Heliport				
	Hangar		200	
	Lounge		150	
	Environment Lighting		1,400	
Telecommunication center				
	Data Room		25	
	Environment Lighting		100	
IT Center				

Location	**Load Group**	**Nb**	**Area [m^2]**	
	IT Room		25	
	Environment Lighting		100	
Offices				
	1 person office	5	100	
	2 persons office	5	150	
	4 persons office	4	120	
	10 persons office	2	100	
	Small meeting room		15	
	Big meeting room		25	
	Board Room		50	
	Car Charging Station		5	units
	Environment Lighting		2,240	
Guest offices				
	1 person office	20	600	
	Small meeting room	10	200	
	Environment Lighting		3,200	
Waste treatment center				
	Waste water treatment		100	
	Municipal waste treatment		100	
	Recycling Sorting		400	
	Medical waste treatment		100	
	Environment Lighting		1,400	
Firehouse				
	Fireman residence		100	
	Offices		30	
	Restaurant hall		50	
	Restaurant kitchen		50	
	Firetruck hangar		100	
	Environment Lighting		660	
Water Pumping				
	Water Pumping		1	units
Police station				
	offices		50	
	housing		50	
	Car Charging Station		2	units
	Environment Lighting		200	

F Production Mix & Optimal Capacities

Table 26: Production mix in kWh for the best energy system of each strategy.

	Baseline	STRAT1	STRAT2	STRAT3	STRAT4
Generators	10,511,580	6,973,108	1,892,794	1,377,585	1,234,440
PV tracking		5,214,570	14,600,797	10,429,141	
PV distr.					9,120,249
Wind turbines				2,775,988	3,701,317
Total	10,511,580	12,187,678	16,493,591	14,582,714	14,056,006

Table 27: Optimal technology capacities for each strategy.

	Baseline	STRAT1	STRAT2	STRAT3	STRAT4
Generators [units]	6	6	6	6	6
PV tracking [kWp]		2,500	7,000	5,000	
Battery Storage [kWh]			25,000	20,000	20,000
Wind turbines [units]				15	20
PV distr. [kWp]					6,000

References

[1] “Developable Private Island in Greece,” [Online]. Available: https://www.cbre-atria.gr/cms/index.php?option=com_content&view=article&catid=1%3Aproperties&id=6475%3Asizeable-developable-private-island-in-greece&lang=en. [Accessed: 25-Oct-2018].

[2] HEDNO, Nikos Hatziargyriou, "Projects for Smartening the Greek Islands", presented at South-Eastern Region Workshop, September 19-20, 2018.

[3] "HomerPro User Manual", August 2016, Available : Homerenergy.com

[4] “How Does an Electric Generator Work to Generate Power?” [Online]. Available: https://www.adeltd.co.uk/blog/how-does-an-electric-generator-work.php. [Accessed: 10-Jan-2019].

[5] “Technology Roadmap Solar Photovoltaic Energy,” International Energy Agency, 2017.

[6] “How Solar Cells Work - Components & Operation Of Solar Cells.” [Online]. Available: https://solarlove.org/how-solar-cells-work-components-operation-of-solar-cells/. [Accessed: 03-Oct-2018].

[7] “Solar Cell, Solar Module, Solar Array,” PVeducation.com. [Online]. Available: https://pveducation.com/solar-concepts/solar-cells-modules-arrays/. [Accessed: 03-Oct-2019].

[8] “How does a wind generator work?,” UKA Gruppe. [Online]. Available: https://www.uka-gruppe.de/en/citizens-and-communities/operating-principle-of-a-wind-turbine/. [Accessed: 14-Jan-2019]

[9] “Gears & Gearboxes 101,” Windpower Engineering & Development. [Online]. Available: https://www.windpowerengineering.com/mechanical/gearboxes/gears-gearboxes-101/. [Accessed: 12-Jan-2019].

[10] International Renewable Energy Agency, "Electricity storage and renewables: Costs and market to 2030", October 2017

[11] “Technical graphics of innovative lithium-ion accumulators by Liotech company.” [Online]. Available: https://www.visual-science.com/projects/lithium-ion-accumulators/infographics/. [Accessed: 20-Jan-2019].

[12] Dr. Gregory L., Plett University of Colorado Colorado Springs, "Algorithms for Battery Management Systems", Available: https://www.coursera.org/learn/battery-management-systems/

[13] U.S. Department of Energy, "DOE Microgrid Workshop Report", 2011

[14] P. Lilienthal, “How to Classify Microgrids: Setting the Stage for a Distributed Generation Energy Future,” HOMER Microgrid News and Insight, 02-Apr-2013. [Online]. Available: http://microgridnews.com/how-to-classify-microgrids-setting-the-stage-for-a-distributed-generation-energy-future/. [Accessed: 15-Oct-2018].

[15] “Microgrid” Wikipedia. 25-Oct-2018.

[16] Ernie Hayden, "Introduction to microgrids", 2016

[17] “Determination of an economically-suitable and sustainable standalone power system for an off-grid town in Western Australia - ScienceDirect.” [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0960148116311533. [Accessed: 02-Nov-2018].

[18] Pashajavid, E. and Shahnia, F. and Ghosh, "Development of a Self-Healing Strategy to Enhance the Overloading Resilience of Islanded Microgrids",*IEEE Transactions on Smart Grid*, 2017

[19] "Isle of Eigg Building Microgrid", [Online]. Available : `https://building-microgrid.lbl.gov/isle-eigg`. [Accessed: 25-Oct-2018].

[20] “Real time data - TILOS Horizon.” [Online]. Available: https://www.tiloshorizon.eu/real-time-data.html. [Accessed: 10-Nov-2018].

[21] “Renewable resort: Greek island to run on wind, solar power | CBC News.” [Online]. Available: https://www.cbc.ca/news/technology/renewable-energy-tilos-greece-1.4791780. [Accessed: 20-Nov-2018].

[22] "L’énergie électrique dans le bâtiment", SIA380/4, 2006

[23] K. Papakostas and N. Kyriakis, “Heating and cooling degree-hours for Athens and Thessaloniki, Greece,” Renewable Energy, vol. 30, no. 12, pp. 1873–1880, Oct. 2005.

[24] Yann Payen, Gauvain Ramseier, “Comparative assessment of electrical generating systems for a Greek island”, 2018.

[25] “Domestic PV Trackers - Hadrian Electrical.” [Online]. Available: `http://hadrianee.co.uk/domestic-pv-trackers/`. [Accessed: 30-Nov-2018].

[26] Jan Van Herle, "Wind energy", presented at EPFL in 2017.

[27] MIT Electric Vehicle Team, "A Guide to Understanding Battery Specifications", 2008

[28] “Cost of electricity by source,” Wikipedia. 27-Dec-2018.

[29] “Climate & Weather Averages in Nisída Arkoúdi, Greece,”, TimeAndDate, [Online]. Available: `https://www.timeanddate.com/weather/@264610/climate` [Accessed: 25-Oct-2018].

[30] La revue de LUX, "Les normes européennes de l’éclairage, 2004, [Online]. Available: `http://www.afe-eclairage.fr/docs/362-ext.pdf`. [Accessed: 17-Oct-2018].

[31] E. Helmers and P. Marx, “Electric cars: technical characteristics and environmental impacts,” Environmental Sciences Europe, vol. 24, no. 1, p. 14, 2012.

[32] “LTS Water ski boat”, LTS Marine, [Online]. Available: `http://www.ltsmarine.com/english/lts-water-ski-boat/` [Accessed: 17-Oct-2018].

[33] “Bankable solar data for better decisions.” [Online]. Available: `https://solargis.com/`. [Accessed: 10-Nov-2018].

[34] “JRC Photovoltaic Geographical Information System (PVGIS) - European Commission,” 26-Oct-2018. [Online]. Available: `http://re.jrc.ec.europa.eu/pvg_tools/en/tools.html` [Accessed: 26-Oct-2018].

[35] “Global Wind Atlas.” [Online]. Available: `https://globalwindatlas.info/`. [Accessed: 23-Nov-2018].

[36] NASA Surface meteorology and Solar Energy database

[37] "East-West ballasted systems." [Online]. Available: `https://www.metaloumin.gr/en/508/east-west-ballasted-systems`. [Accessed: 14-Dec-2018].

[38] E. A. Alsema, "Energy requirements and CO2 mitigation potential of PV systems," Jan. 1998.

[39] "Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey - ScienceDirect." [Online]. Available: `https://www.sciencedirect.com/science/article/pii/S0301421513010719`. [Accessed: 20-Dec-2018].

[40] M. Romare and L. Dahllöf, "The life cycle energy consumption and greenhouse gas emissions from lithium-ion batteries," Stockholm. Zugriff am, vol. 23, 2017.

[41] W. Kenton, "Discount Rate," Investopedia. [Online]. Available: `https://www.investopedia.com/terms/d/discountrate.asp`. [Accessed: 12-Jan-2019].